U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

PRELIMINARY

PROBABLE MAXIMUM THUNDERSTORM PRECIPITATION ESTIMATES

SOUTHWEST STATES

California
Nevada
Utah
Arizona
Wyoming*
Colorado*
New Mexico*

*West of Continental Divide

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xref: thunderstorm records
Precipitation estimates
Flood forecasting

This study of probable maximum precipitation (PMP) from local thunderstorms for the Southwest United States will be published together with general storm PMP estimates covering this region. General storm PMP estimates are the subject of a current study in the Hydrometeorological Branch and will not be in a form for publication until late in 1974 or early 1975. In the meantime, the estimates of this report can be used for small drainages. In the more orographic regions, the general storm PMP values might exceed the thunderstorm PMP for 6 hours for basins as small as 200 square miles in area.

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I. INTRODUCTION

Purpose of report

This report provides generalized estimates of probable maximum precipitation (PMP) for small drainage basins in the Southwest States. By "generalized" is meant mapped values are given covering the study region from which estimates of PMP may be determined for any selected drainages.

The PMP estimates of this report are considered the upper limits of rainfall resulting from summer or early fall local thunderstorms. Such storms, while producing the most intense point rainfalls of record, characteristically show a rapid decrease in rainfall with increasing area.

For large areas, general storm situations provide the greatest rain potential. A subsequent study will complete the project by providing PMP estimates based on general storms. Until such studies are completed, it cannot be determined over how large an area the local thunderstorm will give the highest rainfall amounts. Topographic control, more important in general storms and varying from basin to basin, determines which storm type is most critical. However, based on completed studies in the Northwest States [1] it is believed the local thunderstorm, in general, will produce greater rainfalls than the general storm for durations up to 6 hours for drainages less than 500 square miles in area.

Authorization

A tentative study of generalized thunderstorm PMP was made in 1968 for small basins within the Corps of Engineers Los Angeles District [2a].

Authorization for a more complete study was given in a memorandum from the Office of Chief of Engineers, Corps of Engineers, dated July 8, 1971. This memorandum included notes on a meeting held in Phoenix, Ariz., May 17-21, 1971, at which time the requirements and priorities of various hydrometeorological studies were discussed. One conclusion of the meetings was that a study of thunderstorm PMP for the Southwest States would be given highest priority.

Scope

Primary effort of this study centered on the general area termed the Southwest States between the crests of the Sierra Nevadas (the western boundary) and the Continental Divide (the eastern boundary). To the north, it extends to the southern limits of the Columbia River system, and is bounded by the Mexican border to the south. Within this region, intense rainstorms occur which are concentrated both in time and space. They are not associated with general storm systems identifiable on weather maps.

A secondary consideration was to extend thunderstorm PMP to cover the State of California. Except for the southeast interior drainages of this State, intense local storms are rare. However, extremely heavy short-duration local rains have been experienced at widely scattered locations associated with several different meteorological features, including general tropical storms, and these events produced rainfalls exceeding the PMP depths for the general storm in California given in a previous study [2].

As a result of the current investigation, some adjustments have been necessary to the earlier analysis, most significantly in Arizona and Utah. The present study also develops depth-duration relationships that permit more detailed evaluation of 6-hour PMP for basins than the earlier study.

Section II of this report provides descriptions of meteorological conditions surrounding observed extreme thunderstorm events, and are, in part, supported by marginal storms that suggest probable extension into boundary areas. Interrelationships of terrain with rainfall are described in section III, and the important features leading to the resulting PMP analyses are presented. Section IV covers the development of generalized thunderstorm PMP.

Appendix A gives results of a radar precipitation echo-elevation study, useful in mountainous areas. Appendix B, titled "Antecedent Rainfall," describes a brief study on intervals between record Southwest States thunderstorms. Results are not applicable to the Pacific drainage of California.

II. METEOROLOGICAL ANALYSIS OF EXTREME THUNDERSTORMS

Determination of small-area summertime PMP for a region must consider analysis of the most extreme occurrences of record. A survey of extreme thunderstorm rains within the southwestern region discloses that comparatively few such events have been observed compared to regions to the east of the Continental Divide. Any approach used must necessarily take into consideration transposition limits to the few major events. Meteorological analysis of these events can give guidance to transposition limits, moisture sources, regional variation and other aspects of the rainfall potential.

This section describes the meteorological conditions surrounding the major short-term thunderstorm events within the Southwest for a period of record from about 1890. Also included in this section is a discussion of unusually heavy summer thunderstorm rainfalls reported along the California coast. From the review of all these events, certain terrain characteristics are noted which are important for development of PMP. These characteristics are discussed in a third unit of this section and used to develop a reasonable explanation of necessary conditions for extreme thunderstorm rainfall.

Parameters considered

In order to review the individual major events, a number of variables have been considered of primary importance in evaluating storm characteristics. A description of these along with the source of data used follows.

Pressure patterns. Normal sea-level pressure patterns (solid lines) and 700-mb contours (dashed lines) for the summer months in the Southwest

States region are reproduced in figure 1 [3]. The essential feature of each of these patterns is the location of the surface thermal low-pressure system of southeast California and western Arizona. Comparisons of normal pressure patterns with the broadscale patterns associated with major storms can give clues to features important to heavy rainfall. Little change in position of surface Low is noted during the summer months with July's analysis showing the lowest central pressure, 1005 mb. The thermal Low is a well-known example of a warm-core cyclone sometimes referred to as a "heat Low." The adjustment westward of upper-level anticyclonic circulation at low latitudes during July and August is an important factor in the moisture analysis and will be discussed later.

Surface weather analyses used in this study of major thunderstorm events have been taken from the original copies of the Weather Service series of North American Surface Charts.

<u>Moisture</u>. Adjusting observed extreme rainfall events for the maximum moisture (through depth in the atmosphere) that is possible for the storm location and time of year is one step in most PMP determinations. The ratio of maximum moisture to that during the storm is the factor by which the storm rainfall is multiplied. While actual moisture in upper air soundings would appear to be the best data for adjusting storms to maximum moisture, such soundings are relatively few and not necessarily representative of moisture in a particular storm, especially for isolated extreme thunderstorm events. An additional shortcoming is that upper air soundings are only available for recent storms. An index to moisture is the precipitable water associated with a surface dew point and an assumed saturated pseudoadiabatic atmosphere. Surface dew-point observations are much more plentiful and are

used in this study, as in all hydrometeorological studies, for moisture maximization. It is generally accepted in the analysis of major storms to determine the highest storm dew point that persists over a 12-hour period and compare this with available maximum values [4]. The procedure used for maximizing storm rainfall for moisture, as described in considerable detail by Myers [4a], is the following:

1. Determine the zone of moisture inflow to the storm and reduce surface dew points to the 1000-mb level within this zone.
2. Find the maximum 12-hour persisting 1000-mb dew point in the inflow zone.
3. From the midmonth maps of maximum persisting 12-hour 1000-mb dew pointsinterpolate the value corresponding to place and time (adjusted as much as 15 days towards the warmer season) of the storm of interest.
4. Determine precipitable water for the dew point values obtained in 2 and 3 from Technical Paper No. 14 [5] or other comparable source.
5. The moisture maximizing factor (f_m) is the ratio of precipitable water values from 4, or

$$f_m = \frac{(W_p)\text{max dew point}}{(W_p)\text{storm dew point}}$$

Precipitation. Records of hourly and daily precipitation are published by the Weather Service for networks of stations within each state. There are at least an order of magnitude fewer hourly recording stations than those taking daily observations. In rugged mountain areas, as is the case for most of the Southwest, much bias exists in the distribution of precipitation stations. Almost no stations are on the mountain slopes or ridges; with nearly all located along valleys and the more accessible sites. Because of the sparse density of regular observing stations in mountainous areas, there is a small chance that an extreme rainfall will occur over any observing station. Therefore, most of the extreme rainfalls known to have occurred in the Southwest are the result of "bucket" surveys made after a major flood event.

Terrain. Analysis of terrain features in the vicinity of each major storm has been made from 1:62,500 scale (1 inch = 1 mile) topographic maps and 1:250,000 scale maps having contour intervals of 200 feet.

Major Southwest thunderstorms

The most intense short-period rains of record in the Southwestern United States are listed in table 1. Approximate locations of these storms are shown in figure 2. All of these rainfalls are from either cooperative station reports or from surveys made after the event with one exception. The latter is the 1-hour value of 3.64 inches at Elko. This amount exceeds by far the previous fully accepted maximum 1-hour value for regular recording stations in Nevada (1.50 inches) and approaches the maximum 24-hr value of 4.13 inches also set by this storm (previous 24-hr summertime record for Nevada was 3.45 inches at Alamo, August 1932).

Some of the storms listed in table 1 have been described in earlier reports. Quotations from the observers at Campo, Ft. Mohave, and Chiatovich Flat are given in Technical Paper No. 38 [16], and a meteorological discussion of the Morgan storm is given in Hydrometeorological Report No. 37 [17].

Table 1

Major Short-Period Storms of Record in the Southwest States

Location	Lat (°N)	Long (°W)	Elev (ft)	Date	Duration (min)	Amount (in)	Ref	Remarks
California								
Campo	32°36'	116°28'	2590	8-12-91	80	11.5	6	amount is a minimum
				7-18-22	120	7.1	7	
Vallecito	32°58'	116°21'	1450	7-18-55	70	7.1	8	
Chiatovich Flat	37°44'	118°15'	10320	7-19-55	150	8.25	9	precise location unknown
Nevada								
Elko	40°50'	115°40'	5075	8-27-70	60	3.64	10	
Palmetto	37°27'	117°42'	6700	8-11-90	60	8.8	#	amount questionable
Utah								
Morgan	41°03'	111°38'	5150	8-16-58	60	7*	11	amount questionable
Arizona								
Ft. Mohave	35°02'	114°36'	550	8-28-98	45	8	12	precise location unknown, amount is inexact estimate
Globe	33°20'	110°43'	3540	7-29-54	40	3.5	13,14	
Santa Rita	31°45'	110°51'	4400	6-29-59	60	4.5	15	storm center unknown, amount is a minimum
New Mexico								
None exceeding 2.00 in one hour								

*A catch of 7 inches in a tilted bucket has been judged questionable by a number of field personnel involved with evaluating and verifying the storm. Other measurements from a survey after the storm were 6.75, 5 and 5 inches observed approximately 2 miles southwest of the reported 7 inches. The 6.75 inch value has been used in this report as the maximum storm rainfall.

#From station records [19].

The following paragraphs present particular aspects of each of the storms listed in table 1 and represent the pertinent available information.

Campo, California. The Campo storm of August 12, 1891, was one of the most intense thunderstorms reported within the Southwestern States. Rains fell between 1140 and 1300 PST with the total amount shown in table 1 representing a minimum; since, the observer reported the gage overflowed at least once and that it was subsequently washed away by a flash flood.

This storm produced the greatest rainfall depth, for the short duration, reported in the Southwest over the available records of 80 years. The Ft. Mohave and Morgan, Utah, storms gave approximately the same rain intensities but were of shorter duration.

Rather spotty surface reports for this early year indicate a thermal low-pressure system east of the Coast Range extending from the Gulf of California northward into Nevada, figure 3. The Low was considerably deeper (998 mb) than normal (1010 mb) and oriented more towards N-S than normal. Although thermal Lows are customarily attended by weak circulation patterns, there is evidence that a layer of moisture with dew points (reduced to 1000 mb) above 70°F extended into the Campo vicinity from the Gulf of California.

One may speculate on possible increase in rain due to the terrain in the vicinity. Campo is in a broad valley at about 2600-ft. elevation with higher elevations (about 3000 ft) within a few miles in most directions except for less than a 200-ft increase in elevation in the broader Campo Valley to the north-northeast and lower elevations than Campo to the south and southeast. The higher elevations may have triggered off the thunderstorm that then drifted over Campo. An extract from the observers notes, "... and then another cloud came up and the one that had first passed over drew back and the two came together and it poured down whole water nearly...,"* could indicate movement of the storm.

A suggestion that Campo is a preferred location for intense thunderstorms may be inferred from the fact that a second extreme rainfall, 7.1 inches in 2 hours, occurred there on July 18, 1922. On the same date 5.01 inches fell in 90 minutes at Squirrel Inn, Calif. (about 125 mi NNW of Campo) [7]. Few storms in California have exceeded this intensity. Figure 4 shows the near normal pressure patterns for several days before and after the storm. In order to evaluate any preference, comparisons were made of the series of annual maximum 1-day rain amounts for the nearest stations on the east slopes of the Coastal Mountains. Boulevard (approximately 9 miles ENE of Campo) had 10 years of simultaneous record; Borego (approximately 45 miles north of Campo) had 8 years; and Ranchita (approximately 40 miles north of Campo) had 11 years. Frequency plots of each of the series indicate higher values at Ranchita and Boulevard than at Campo. The graphical comparison with Borego indicates somewhat higher values at Campo. These results are presented in terms of return period in table 2, along with comparative results for two stations west of the ridgeline. It is concluded that the two outstanding events at Campo were chance occurrences and not due to a favored terrain setting with at least equal likelihood that such events are possible within about 50 miles of Campo. Nevertheless, the occurrence of a Campo-like event is believed limited generally to any of the easterly slopes in these southern California mountains exposed to moisture from the Gulf of California.

*Quotation altered to correct misspelled words.

Table 2

Comparison of 10-Year Return Period Rainfalls for Campo, Calif. and Selected Stations

Station	Elev (ft)	Years of record concurrent with Campo	10-Yr Return amt (inches)
Campo (E)*	2590	15	1.10
Alpine (W)	1860	11	0.82
Ramona (W)	1500	15	0.80
Ranchita (E)	3500	11	2.00
Borego (E)	500	8	1.40
Boulevard (E)	3200	10	1.37

*Station west (W) or east (E) of ridgeline

The areal extent of the rainfall at Campo on August 12 cannot be determined with much confidence. San Diego, about 40 miles west, had no rain for the day. One clue is in an eyewitness account of an observer, 1-1/4 mile from Campo, who had about 3 inches of rain from the storm.

Ft. Mohave, Arizona. A significant thunderstorm occurred at Ft. Mohave on August 28, 1898. Only a brief description by the local observer is available to indicate the severity of this storm. His account states in part that "... between the rain and the furious wind, my rain-gage was upset." An estimate of the amount which fell in the 45-minute storm is the 8 inches measured in a previously empty wash tub.

Only a minimum of weather records are available to describe the synoptic patterns. The thermal Low existed in almost the normal position and seems to have been only slightly more intense than normal. The storms appears to be another example of high moisture brought northward from the Gulf of California by circulation associated with the thermal low-pressure system. Synoptic weather charts for August 26-29 are shown in figure 5. A warm (maximum temperatures over 90°), moist (dew-point temperatures 72°F) tongue of air penetrated northward from the Gulf of California towards Salt Lake City. Phoenix, the nearest first-order Weather Station, reported thunderstorms and showers. The chart for the 29th indicates the thermal trough had intensified with a maximum temperature above 100°F. Combined with the high moisture,the potential for instability was increased.

Unlike the other major storm events listed in table 1, the Ft. Mohave rainfall was centered over comparatively flat terrain of near 550-ft elevation in the north-south oriented Colorado River Valley. Although the precise location of the Ft. Mohave station is uncertain, there is no terrain above 1000 ft within 5 miles of the most likely position. To the east and west, ridges at about 10 miles distance reach to nearly 3000 ft. Of the rainfalls listed in table 1, this one occurred in the least rugged terrain setting.

Globe, Arizona. Scattered thunderstorms occurred throughout eastern Arizona on the afternoon of July 29, 1954, with a maximum reported rainfall of over 3.5 inches in about 40 minutes near Globe. Reports of 24-hour precipitation amounts at other Arizona stations on the 29th and 30th are shown in figure 6a. Figure 6b shows an expanded portion of the map for the vicinity of Globe. It is apparent that the precipitation was limited to the eastern half of the state. An amount exceeding one inch was noted near the Arizona-New Mexico border and within about 75 miles of Globe. The value of 1.1 inch reported at Globe is part of the heaviest rain centered about 3 miles to the south. The rain began about 1810 MST and was heaviest during the first 20-45 minutes although some light rain continued another 10-15 minutes.

Surface weather patterns shown in figure 7c indicate that for July 29 the thermal low-pressure system had broadened and shifted northward from the previous 24-hour position although it remains close to the July normal (figure 1b). Low-level moisture from the Gulf of California probably was brought into the southeastern quadrant of Arizona during the shift in the thermal Low. Dew-point temperatures reduced to 1000 mb are between 65 and 70°F in southern Arizona or about 10°F below the maximum persisting 12-hour amounts determined for this area.

The circulation at 500 mb, in figure 7d, was anticyclonic about a center located near the Four Corners region. The pressure pattern at 700 mb (not shown) was probably responsible for bringing upper level moisture into the Globe area from the Gulf of Mexico.

The area around Globe is very rugged with many abrupt slopes and canyons marring the terrain. Pinal Peak (7850 ft) is the highest of a number of terrain prominances lying 6 miles south-southwest of Globe. The heavy rainfall occurred on the north-facing slope at about 4000 ft elevation. The thunderstorm of the 29th moved into the area from the east,intensfying as it pushed against the mountains, and subsequently dissipated after passing over the Pinal Creek watershed.

Vallecito, Calif. A heavy thunderstorm rainfall at Vallecito accumulated 7.1 inches of rain (measured in a tub) in 70 minutes on July 18, 1955. A glass six-inch tube rain gage at the site overflowed. The rain in the vicinity of Vallecito began about 1400 PST and continued until roughly 1530

PST, with a witness commenting that the storm movement was from the north-northwest.

Vallecito Creek flows eastward from the Laguna Mountains of the southern California Coastal Range. The center of the heavy precipitation occurred in the Vallecito Creek basin between the Vallecito Mountains (3000 ft) to the north and the Tierra Blanca Mountains (2-3000 ft) to the south. At this location the valley appears to narrow relative to its width both to the east and west. For moist flows from the east, this constriction contributes to vertical motion by forced convergence and may have been in part responsible for the location of this heavy rain event.

Surface weather maps for the period indicate a trough of low pressure extending from Yuma northward to central Nevada (figs. 8a-c) at considerable displacement from the normal position. Moist unstable air covered Arizona on the 17th and extended both westward and northward during the 18th and 19th. The circulation pattern at 700 mb on the 18th, figure 8d, showed a westward flow along the U.S.-Mexican border. In the vicinity of southern California, convergence is encountered with a northwesterly flow from the Pacific. The pattern continued through the 19th with the Gulf of Mexico air turning more to the north over southern California and the zone of convergence with Pacific air occurring along the Sierra Range. At 500 mb over southern California, a study of air flow suggests a well-defined upper level front contrasting southwesterly flows to the west and easterly flows to the east of this line.

Stations at El Centro and Thermal, Calif., reported dew-point temperatures (reduced to 1000 mb) above 70°F from 1930 PST July 17, until the time of the Vallecito storm on the 18th. Average 12-hour persisting dew points during this period approached or equaled the maximum 12-hour persisting 1000-mb dew-point value of 73° for this region and month.

According to the state climatologist [18], "there was considerable thunderstorm activity in the Southeast Desert Basins from the 18th through the 24th which spread northward into the Sierras on the 21st and 22d. Thunderstorms with attendant strong winds and heavy rains spread some damage in San Diego and Imperial Counties on the evening of July 18th." The 2.34-inch rain at Twentynine Palms, 2.18 inches at Beaumont Pumping Plant, and 1.05 inches at Palm Springs were measured on the 19th, but almost all occurred on the 18th. The center of these heavy rains is about 80 miles north of the Vallecito location. The extensive thundershowers on the 18-19th are shown in figure 9.

Chiatovich Flat, California. A fortuitous observation by a graduate student with a portable rain gage resulted in a measurement of 8.25 inches in approximately 2.5 hours on July 19, 1955. Efforts to verify this observation have not disclosed any additional information.

The movement of the moisture flow to a more northward path discussed above in the Vallecito storm probably was operative in producing an unusually heavy rainfall at Chiatovich Flat on the eastern slope of the White Mountains along the California-Nevada border. The network of precipitation stations north of 36° latitude in California did not report any rain occurring on the 19th. Therefore, the isolated heavy thunderstorm rainfall at Chiatovich Flat appears unusual for this date as no station within 200 miles reported rain.

From examination of the precipitation records for the 20th, shown on figure 10, and subsequent heavy rains on the 21st and 22nd, it is concluded that considerable moist air penetrated to the vicinity of Chiatovich Flat prior to these dates. The observer at Mono Lake (about 40 miles northwest of Chiatovich Flat) reported [18], "... heavy rain started about 3:00 p.m. July 21st lasting to around 5:30 p.m. (with a total of 2.50 inches falling in this period). A heavy cloudburst broke over the mountains to the west of Mono Lake coming down all of the canyons, particularly the canyon above Tioga Lodge, which suffered immense damage to buildings and grounds estimated at around $150,000."

The above flow of moisture is supported by evaluation of the surface dew points (reduced to 1000 mb). Stations at Blythe, Needles and Daggett report reduced 3-hourly values of 70°F. Farther north the high moisture is not discernible in the hourly records with most values ranging in the mid 60's. An extreme point value (reduced) of 74°F occurs at Bishop the morning of the 20th that may be indicative of the continuation of the moisture toward the Mono Lake area.

Chiatovich Flat is near the crest of the White Mountains which extend upward to peaks exceeding 13,000 ft to the northwest and 14,000 ft to the southwest. The White Mountains are a short range oriented north-south to the northeast of Bishop. Only 4 miles to the east at the base of the mountains, the elevation drops to 5800 ft. Moist air from the Gulf of Mexico above 700 mb (10,000 ft) approaching this range from the east could easily provide sufficient unstable air to result in thunderstorms along the east face of the mountains. Moisture at such high elevations would find few obstacles necessary for forcing vertical motion and convection except for the White Mountains and the Sierra Nevada ridge. Because of the absence of observations at these high locations, any thunderstorm rains would probably go unreported, except for a chance situation as occurred at Chiatovich Flat.

Figure 11 shows the weather maps surrounding the time of the Chiatovich Flat storm. Little variation is seen in 11c from the conditions 24 hours earlier shown in 11a (Vallecito storm). Aloft, the intensification of anti-cyclonic circulation over California and Nevada, and the approach of an offshore trough vary from the previous map shown in figure 9d.

Morgan, Utah. A severe thunderstorm dumped about 7* inches of rain slightly east of Morgan (Round Valley) on August 16, 1958. This rain fell in about 1 hour over a relatively small area. Except for 1.19 inch 24-hr total at Wanship Dam (about 25 mi to the SE), amounts less than .25 inch were reported elsewhere along the mountains of northern Utah (see fig. 12). Local witnesses reported [11], "... heavy black clouds formed over Henefer about 7 miles to the southeast and over Stoddard about 5 miles to the northwest. Each appeared to move toward the Round Valley area."

Analysis of surface conditions, figures 13a-c, indicates a rather loose pressure pattern throughout the Great Basin area between the 15th and 17th, not unlike the August normal pattern. The air at low levels was unstable as shown by the widespread showers and cumulus developments reported over a wide area.

The storm center was about two miles northeast of Morgan in Round Valley and roughly 15 miles southeast of where Weber Canyon cuts through the Wasatch Mountains. Within 5 to 10 miles in most directions, peaks rise 3000 feet above the valley base. The overall terrain in the vicinity of this storm is extremely rugged in which it is common for severe thunderstorms to form and drift across the valleys.

*See note, table 1.

An inflow of very moist air was traced northward from Yuma through chronological sequences of dew-point temperatures at intervening stations. Surface dew points, reduced to 1000 mb, indicated 12-hour mean values of 73°F occurred at Yuma between 2300 MST of August 13 and 2000 August 14. High dew points spread to Prescott between 1700 of the 14th and 1400 of the 16th and were noted at Cedar City, Utah, between 1100 and 2000 of the 16th. Marginally high dew points were observed at Las Vegas but not at other more northerly Nevada stations. In the Salt Lake City-Ogden area, the highest reduced dew point is 69°F between 2000-2400 of the 16th, which is about four degrees below the maximum 12-hour persisting dew point for this location in August. The 12-hour persisting dew point immediately prior to the Morgan storm was 62°F at Salt Lake City, roughly 10 degrees lower than the maximum for this location.

The circulation at 700 mb, shown in figure 13d, brought increasing moisture in a deep layer between 1700 MST on the 16th and 1700 MST the 17th. The apparent source of this high-level moisture was an inflow of tropical air from the Gulf of California. Even the circulation at 500 mb suggests flows from this source; however, combined with Gulf of Mexico moisture. Vertical temperature-moisture soundings, figure 14, taken at Salt Lake City at 1700 MST on the 15th and 16th are believed to be representative of upper level conditions over Morgan, and indicate that a highly unstable layer of moist air occurred above 650 mb (approx. 12,000 ft) on the 16th. It is apparent that considerable lifting is required to initiate convective instability because of the relatively dry air indicated at lower levels. An increase in low-level moisture at Morgan could have resulted from prior showers. However, once convection was initiated, the moist upper layers contribute fully to cause a maximum precipitation event.

Santa Rita Experimental Range, Arizona. At the southern edge of the Santa Rita Experimental Range, Arizona, 4.5 inches of rain fell in about 55 minutes on June 29, 1959. This Range is approximately 20 miles southeast of Tucson, Arizona. It would appear that higher rainfalls may have occurred farther south beyond the dense rain-gage network. The rains began at about 1700 MST.

The Santa Rita Experimental Range is on the northwest slopes of the Canelo Mountains about 30 miles north of Nogales. About 5 miles to the south, peaks rise above 9000 feet in the Santa Rita Mountains while sloping gradually down to the Santa Cruz River to the northwest.

No rains were observed on the 28th in this part of Arizona, and the reports of precipitation for the State on the 29th were limited to the southeast corner of the state. Figure 15 shows daily totals for the 29th throughout Arizona. In addition to the downpour at Santa Rita, heavy showers (1.60, 1.89, 1.73, 1.07, and 1.12 inches) were reported at distances between 40 and 100 miles away. High moisture conditions continued into the next day as indicated by many of the stations in southeastern Arizona reporting showers, but none exceeded one inch.

Analysis of reduced surface dew point showed a maximum at Yuma, Tucson, Douglas, and El Paso, between 1700 on the 28th and 1100 on the 30th. The instantaneous maxima were between 68° and 73°F. The maximum 12-hour persisting values of 70°-74°F determined for this area and date are more than 10 degrees higher than the highest 12-hour persisting values surrounding this storm. Since the dew-point maxima occurred nearly simultaneously at Tucson and Douglas, it is belie that the moisture inflow was from the south to southwest around the quasi-stationary thermal Low centered near Las Vegas.

The surface analysis for June 29, 1959, shown in figures 16a-c, indicates that a weak stationary front lies east-west through the Four Corners region. The position of the thermal Low is roughly 300 miles farther north than on the normal June map (figure 1a). Low-level moisture carried by the west to south-west winds from the Gulf of California is forced to rise by the Santa Rita mountains and low-level convergence.

At 700 mb the circulation was primarily from the southwest although there was the suggestion along the Southern Arizona-New Mexico border of high-level convergence with air from the Gulf of Mexico at about the same time of the heavy rain event at Santa Rita. The 700-mb pattern is shown in figure 16d.

Elko, Nevada. Another example of extreme moisture carried far inland, as in the Morgan storm, is a particularly heavy rainfall of 3.64 inches in 1 hour (3.47 in clock hour, 1200-1300 MST, and 4.13 inches in less than 4 hours) at Elko, August 27, 1970. This amount is the greatest 1-hour value at Elko in a record extending over 100 years and is of interest especially in that Nevada otherwise has few cases of summertime, 24-hour amounts greater than 3 inches (none in the last 25 years). The 24-hour (4.13 in) and monthly total (4.61 in) also were new records for Nevada summer months. The previous 1-hour and 24-hour maximum August rainfalls at Elko were 0.55 and 1.50 inches, respectively.

Elko is situated in a northeast-southwest valley of the Humboldt River, between ridges whose peaks exceed 6000 feet roughly 5 miles distant on either side. Peaks to 7500 feet occur within 10 miles surrounding Elko, while the

Ruby Mountains 20 miles to the southeast, contain peaks exceeding 11,000 feet.

No significant synoptic feature that may have brought about this unusual occurrence was apparent on the surface weather maps (see figure 17a-c). The thermal low-pressure center is near its normal position and it's possible that moist low-level air from the Gulf of California penetrated into the valleys of central Nevada.

Maximum instantaneous dew-point temperatures at Ely and Tonopah, when reduced to 1000 mb, yielded values of 68° and 71°, respectively. Twelve-hour persisting values were more than 5 degrees less than the maximum 12-hour persisting dew points of 72° determined for this location and date. There was some evidence, through the large shower amounts in central and southern Nevada on the previous day, that a layer of considerable moisture moved northward from the Gulf of California.

Winds at 500 mb, shown in figure 17d, appeared to be steady from the southwest over the previous 48 hours as part of the upper level anticyclone over eastern Colorado. This circulation probably reinforced the low-level moisture inflow pattern from the Gulf of California.

Palmetto, Nevada. Roughly 35 miles southeast of the Chiatovich Flat storm there was a report [19] of an 8.8-inch rainfall in 1 hour at Palmetto, Nevada, August 11, 1890. The location of this event is at about 6700 feet in a valley to the north of the Last Chance Mountains. To the northeast and within 5 miles of the approximate location of the storm center there are no peaks that extend upward to over 9000 ft. The lowest elevations slope off to the northwest.

It is unfortunate that, at this early date, insufficient data were available other than to permit a sketchy description of surface conditions as shown in figures 18a-d. The patterns for this series show the thermal Low located somewhat more to the north than normal; however, these positions may suffer from the sparse data.

The Palmetto storm was believed questionable in table 1 because so little information was available and the total rainfall amount has been considered erroneous, according to the discussion in Weather Bureau Technical Paper No. 38 [16]. Nevertheless, flooding and local damage did occur, and the observations accompanying this report fit a pattern noted in other major events (see discussion appendix C).

Discussion of thunderstorms in the Southwest

As a result of the foregoing documentation of intense summer thunderstorm rainfalls in the Southwest, it is apparent that these storms are, without exception, very local in extent compared to those in the Eastern United States. On a few extreme occasions, scattered showers are noted over a large area, as was the case for the Vallecito, Morgan, and Globe storms. What then appears as a primary question is: How and why does an extreme event occur where it does in an air mass of seemingly homogeneous moisture, instability, and winds? The answer to this question is not directly obtained from the available information. The following discussions are concerned with comments about (a) the general situation that is observed in the Southwest, and (b) conditions that are important in bringing about extreme situations. Both the general (a) and the extreme (b) commentaries are given for discussions of synoptic weather-, moisture-, and terrain-conditions.

Synoptic weather conditions. (a) Particularly in Arizona is the summertime thunderstorm significant. The singularity of the summer rainfall cycle in Arizona has been well established in the literature of southwest climate. Bryson and Lowry [20] make reference to the "Arizona Summer Monsoon," that on the average is initiated between June 26 and July 4 of each year and lasts into early September, according to Jurwitz [21]. The phenomenon is explained as the rapid transition from one dominant air mass situation to another. The "monsoon" is not always of the same intensity and in some years may be indistinguishable. The following sequence of events are noted to result in circulation favorable to summer thunderstorms over Arizona.

1. The eastern Pacific and Bermuda anticyclones are centered near 30°N in late spring.

2. The mid-latitude jet stream (near 300 mb) which has prevailed near 35°N in late spring shifts northward toward the end of June.

3. The eastern Pacific anticyclone builds northward and eastward to bring comparitively drier northerly air to the Coastal States. The Bermuda anticyclone also expands, northward and westward, as a result of step 2.

4. The west extension of the Bermuda High permits occasional penetrations of a deep layer of moist air northwestward over Arizona.

The areal extent of the influence of the summer monsoon in the Southwest has been stated by Bryson [22] as between the Rocky Mountains on the east, the Sierra Nevada on the west, the Sonora Desert of northwestern Mexico on the south, and a zone at about 40°N latitude on the north. North of this zone the dominance of summertime precipitation rapidly diminishes.

At the surface the general condition is shown by the position of the thermal Low in figure 1. In the mean of the four months shown, the center of the Low is just to the east of Yuma, Arizona. Because of the weak pressure gradient normally attending this low-pressure system, little support exists for other than local winds.

(b) The occurrence of extreme thunderstorms in the Southwest is, for the most part, indistinguishable in terms of apparent differences in synoptic pressure patterns from the normal. This conclusion comes from a study of the intense storms in section II. At the surface, the position of the Low is slightly north of its normal position at the time of the Globe, Vallecito, and Santa Rita events. One possible result of such a northward shift is to permit a greater pressure differential to develop between the lower Gulf of California and the Southwest desert that would contribute to bringing surges of low-level moisture into the Southwest [23]. However, this feature is not apparent in the other extreme events studied in this report, and its usefulness as an indicator of these extremes is minimal.

Moisture sources. (a) The problem of moisture sources is a complex one in the Southwest, and the logical sources are the tropical air masses occurring over the Gulfs of California and Mexico. Much study of the relationship between moisture and pressure patterns has shown that typically there is a moist tongue of air flowing to the north and rising along an isentropic (constant potential temperature) surface around the western portion of an antycyclone. Byers [24] indicates that in "... the mountain and plateau region of the West it has long been recognized that summer rains and thunderstorms are associated with the positions of the moist tongue on the 312° to 318°A surfaces." Over the Southwest this leads to moist air sliding upward to levels above 700 mb as a consequence of the circulation around the Bermuda High.

The Gulf of California represents a second source of moisture. Circulation patterns conducive to bringing moisture into the Southwest are found in the summertime thermal Low that prevails over the Southwest (figure 1). Moist air associated with this source region is a low-level occurrence in contrast with the upper level moisture from the Gulf of Mexico.

Moist air that approaches the dry adiabatic lapse rate is conditionally unstable. Provided that the layer is moist (not necessarily saturated) and sufficient lift is supplied for the air to attain the level of free convection, cumulus development occurs. The height of development is controlled by the degree of stability of the upper levels. Maximum height is obtained with maximum moisture and if no impeding stable layers exist up to the height of the tropopause.

In the Southwest, afternoon thunderstorms are most frequent during the summer months. Studies have indicated that they are initiated in conditionally unstable air by thermal heating of ridges and mountain slopes and grow with time until sundown when the source of convection is terminated. Widespread thundershowers during July and August in the Southwest attest to the available moisture, instability, and the needed stimulus. Sufficiency of moisture at lower levels of the atmosphere is always the determining factor as to whether cumulus development does or does not appear under otherwise comparable conditions.

Another characteristic of summer thunderstorms in the Southwest related to moisture is their inefficiency for producing rainfall at the surface. The relatively high cloud base level, compared to similar storms in other parts of the country, results in a large part of the precipitation that falls in these regions evaporating. Some estimates show as little as one-fourth the rain at cloud base reaching the ground from normal summertime storms.

(b) Regarding extreme thunderstorm moisture, the amount of precipitation that falls from a particular event is a function of available moisture and condensation nuclei, the depth of saturation, the rate of moisture inflow (resupply), convergence of available moisture, and the height of convective development. It follows that any or all of these factors should approach their maximum in any PMP-type storm. Maximum available moisture occurs nearest the gulf sources. The greatest moisture in depth is likely when low-level inflow coincides with the location of the moist upper level flow. The maximum rate of resupply is likely when the surface pressure gradient between the lower Gulf of California and the thermal Low is greatest.

Thunderstorm efficiency is increased when evaporation losses are reduced. Natural ways in which evaporation processes are reduced or slowed are to increase moisture in the below-cloud layers from the occurrence of prior showers, precipitating larger droplets, protecting the core of precipitation by broader rains, that is, fatter clouds, and by lowering the level of the cloud base. Of these possibilities, low base, fat thunderstorms appear to be the most likely maximum rainproducers in the Southwest.

Storm 12-hr persisting dew points reduced to 1000 mb appear to be considerably less than the maximum persisting 12-hour values for the locations of events in this study. These values more closely approach the maxima within about 300 miles of the Gulf of California. Otherwise, isolated peaks of maximum moisture are difficult to distinguish in the sparse data network, and it may be necessary to analyze dew points over a shorter time interval for these local storms than for general-type storms.

An additional consideration is storm movement. The greatest storm rainfall at a point is probable when the thunderstorm remains stationary, or nearly so, in space. As the basin area increases, the necessity for minimal movement decreases.

Terrain conditions. (a) Terrain exerts considerable influence on the moisture flows from the Gulfs of California and Mexico. The Rocky Mountains and their extension into Mexico present a major obstacle to low-level flows, and the moist air from the Gulf of Mexico must rise above 7000 ft to clear the terrain at its lowest elevation. In so doing, the initially deep moist tongue is raked from below by the rugged terrain features such that rivers or streamers of moist air with bases between 7000 and 10,000 ft remain to penetrate over the Southwest.

The effects of terrain also interfere with the direction of low-level moisture from the Gulf of California causing it to meander thru channels of ridges in order to infiltrate interior regions. Terrain features also act to constrain movement of moist air layers, causing local concentrations of moisture at low levels.

(b) If an extreme rainfall event is to take place in the complex terrain of the Southwest, it is necessary to develop a condition that will provide maximum moisture throughout depth. Upper level moisture is brought into the Southwest from the Gulf of Mexico. Because of the Rocky Mountains, this moisture is most often noted above about 10,000 ft over the Southwestern States. The occurrence of pockets of low-level extreme moisture along with intrusions of mid-level moist unstable air provide a condition for maximized moisture through depth. Terrain features also act as mechanisms for forced convergence and lifting when properly oriented to low-level inflow. Therefore, it is to be expected that the greatest probability for PMP thunderstorm occurrence will be in a terrain convergence basin exposed to direct moisture inflow.

Significant inflow is important only for PMP considerations on the order of 6 hours.

The fact that the extreme occurrences are mostly of durations less than a few hours can be explained by lower level moisture becoming exhausted with no large-scale rigorous moisture inflows. The sheltering effect of terrain barriers is perhaps the best restriction to low-level inflows to interior regions.

With the exception of the Ft. Mohave storm, all extreme short-duration thunderstorm rainfalls have occurred in rugged mountainous terrain in the Southwest. This fact is most important in limiting the extent of transposition of storms within this region.

<u>Thunderstorms in the coastal drainage basins of California</u>

Isolated thunderstorms comparable to the major events described in the previous section rarely occur west of the Sierra Nevada range or north of the Tehachapi Mountains. It is believed that the reason lies in the inadequate supply of necessary warm, moist air at low levels to this area during the summer months of June to September. In general, the Eastern Pacific high-pressure system results in light north-northwesterly flow along the coastal slopes. Surface heating of the stable marine air is insufficient to induce strong convection in summer.

A number of instances of extremely heavy short-duration rains have occurred along the California coastal mountains, particularly at the north end of the Sacramento Valley during the transition period of late spring or early fall. In almost every case these events are associated with a more general-type storm although they result in significant anomalies to the continuous rains of the general storm. The peak isohyetal patterns within the general rainfall distribution are very local in extent and in this characteristic are similar to isolated thunderstorm patterns elsewhere in the Southwest.

It has been necessary to include these heavy rain events in the present study in order that evaluation of short-duration PMP can be extended to the coastal bounds. Evaluation of thunderstorm PMP for California completes the PMP studies for California. Larger area PMP are given in HMR No. 36 [2].

Most of the intense isolated California thunderstorms are described in HMR No. 37 [17]. Table 3 lists some pertinent facts about these storms. Four of these events were associated with tropical storms. Most of the discussion following the table concerns tropical storms of record, important to the Southwest.

Table 3
Short-Duration Thunderstorms Along California Coast

Location	Elev.	Date	Duration	Amount
Encinitas	100	10-12-89	8 hr	7.58 in.
Kennett	730	5-9-15	8	8.25
Wrights	1600	9-12-18	1	3.5
Red Bluff	307	9-14-18	3	4.70
Tehachapi	3975	9-30-32	6.5	4.38
Avalon	50	10-21-41	3.5	5.53
Los Angeles	500	3-3-43	3	3.32
Newton	700	9-18-59	5	10.6

The storms at Kennett, Avalon, Los Angeles, and Newton were imbedded within cool-season general rains lasting more than 24 hours. These unusual events differed from other low-latitude storms in that they contained exceptionally high moisture as a result of pulling air from more tropical latitudes. As this air of high moisture content is convectively unstable, thunderstorm activity is initiated as the air is lifted over the coastal mountains or by frontal action. Strong convergence at low levels acts to intensify instability in some cases resulting in these unusual rainfall amounts.

The thunderstorm events at Wrights, Red Bluff, Tehachapi, and Encinitas were associated with decadent Eastern-Pacific tropical cyclones. Intrusions of unstable moist air far in advance of the storm centers often result in extensive summer rains throughout the Southwestern States. The storms develop over the warm waters off the lower west coast of Mexico and move northwestward along the coast. Most of the storms move on to the west under the dominant influence of the easterlies. Only rarely do tropical storms move north off the California coast since the cold surface water quickly depletes the storm's energy. A few, however, recurve north and northeastward crossing the coastline of Baja and southern California. Once on land the fury of their winds rapidly dissipates against the foothills while the moisture is advected northward into the southwestern region. The moisture from these tropical storms often extends hundreds of miles ahead of the last reported position of the organized storm and on a few occasions the resulting precipitation often in the form of thundershowers appears unrelated to the distant southerly sources.

Although tropical storms in the Eastern Pacific have not had the study given to Atlantic hurricanes, the severity of these storms has often brought heavy rains and considerable damage to southern California and Arizona.

Hurd [25] and Rosendal [26] have attempted to chronicle these storms but admit the records are incomplete since the offshore area is not a region of frequent ship reports. From their records, however, it appears that about seven tropical storms occur each year of which three attain hurricane force. Less than one storm per year, on the average, strikes the coast and perhaps a dozen have brought damaging floods to the southwest during the past 25 years. Storm tracks of the more notable occurrences are shown in figure 19. Brief discussions of those storms for which short-duration heavy rain were reported are given in the following paragraphs.

During September 1939, six tropical storms formed off the Mexican Pacific Coast. One of these was of special interest because it brought heavy rains to a populated area, moved northward along the coast, finally crossing inland about 0800 PST on the 25th. Damage along the coast of California alone was estimated at 1.5 million dollars. Mt. Wilson's rainfall was over 11 inches between the 24th and 26th. Discussion of the storm is given in HMR No. 37 [17]. About 12 hours prior to the onset of rains at Los Angeles, a series of intense thunderstorms erupted over Indio, California in the Coachella Valley [17]. Within 7 hours, 6.8 inches of rain had been measured. The moisture contributing to this event was believed associated with the tropical storm off the coast of southern California.

A severe, damaging tropical storm for coastal communities and one which traveled extremely far north occurred September 12-14, 1918. The storm track, figure 19, shows the storm movement off the coast to central California, where the surface circulation dissipated because of passage over the cooler surface waters. Moving inland south of San Francisco, this storm brought strong extensive rains to central and northern California; 8.75 inches in 24 hours at Wrights and 4.7 inches in 3 hours at Red Bluff. For additional details, the reader is referred to HMR 37 [17].

Another heavy short-period rainfall occurred at Encinitas, California, about 25 miles north of San Diego, October 12, 1889 [47]. The account states that an intense evening thunderstorm produced 7.58 inches of rain in 8 hours, while only .44 inches and .04 inches were observed at San Diego and Los Angeles, respectively.

Although little information is available concerning the weather conditions for this early storm, a chart of low-pressure storm tracks for October 1889 shows that a storm moved north off the coast and inland near Monterey on the 12th. The discussion of this storm reports the extensive and heavy rains brought to northern California and that this storm crossed the Rockies, eventually passing across the country into the St. Lawrence region. There is no apparent indication of cause for the Encinitas rainstorm on the surface analysis for this date, but it is presumed to be associated with the passage offshore of the tropical disturbance.

Other tropical storms have moved north along Baja California and into southern Arizona. A few of the most recent major storms were those of August 25-29, 1951, August 24-27, 1953, September 10-12, 1959, September 7-11, 1961, September 5-11, 1964, and September 11-15, 1966. One of the most extensive rains to come from a tropical storm in the Southwest was the record-setting storm of September 3-6, 1970 [27, 28, 29]. Moisture spread far ahead of the surfact center, was lifted aloft isentropically. It resulted in widespread cloudiness and in a new 24-hour precipitation record of 11.4 inches at Workman Creek, Arizona, between 2200 MST on the 4th and

2200 MST on the 5th. Six-hour amounts of 4.00 inches between 0600 and 1200 MST on the 5th at Workman Creek attest to the locally intensive effects of orographic lifting in storms of this type.

III. VARIATION OF THUNDERSTORMS WITH TERRAIN FEATURES

The influence on thunderstorm development and shower precipitation of terrain is well documented for the summer rain season in the Southwest. The frequency of such storms is considerably higher along slopes than in the flatter terrain. Whether there is a difference in the potential rain magnitude of the storms over the Southwest States is a more difficult problem. This section studies the relationship between terrain and extreme short-duration rainfall data and makes some conclusions on the relative significance of terrain to the PMP thunderstorm. Because so few extreme thunderstorm rain events have been observed in the Southwest (six values over 5 inches in a few hours) the evaluation of terrain effects was done primarily through analysis of much more abundant but less intense maximum 1-hour recorder rain amounts.

Terrain roughness. In a recent study of PMP for the Tennessee River drainage [30], a relationship between thunderstorm rainfall and terrain roughness appeared to be evident in the recorded data. Many 3- to 4-hour thunderstorm rains (36 cases with 5 inches or more) were available from bucket surveys. As a result of the TVA study, it was believed that a terrain roughness versus rainfall relationship would be most apparent in regions where considerable differences in the degree of roughness exist.

The initial study was of 36 recorder station values in Arizona. Averages of the maximum 1-hour and 6-hour amounts of record at each station for the months of June through September (four values in each average) were used as the "stable" statistic. The period of record ranged from 10 to 30 years.

The terrain surrounding each station was classified as "rough" where a change in elevation of 150 feet or more occurred in 1/4 mile, as "intermediate" with an elevation change between 50 and 150 feet in 1/4 mile, and "smooth" with elevation change less than 50 feet in 1/4 mile. A 1:250,000 scale map was used for these classifications. Any slope within a 1-mile radius of each station was considered. The rainfall maxima were selected from short-duration storms (based on the criteria listed in table 7, described on page 58). The average maximum 1-hour and 6-hour values within each terrain classification are listed in table 4.

Table 4

Terrain Roughness* Versus Average of Maximum Recorder Rainfall

	Smooth	Intermediate	Rough
Arizona (36)			
1-hr	1.57 (15)	1.73 (10)	1.95 (11)
6-hr	2.24	2.30	2.58
Utah (33)			
1-hr	0.81 (12)	1.06 (11)	1.05 (10)
6-hr	1.18	1.22	1.54
Nevada (23)			
1-hr	0.87 (10)	1.45 (6)	0.69 (7)
6-hr	1.27	1.67	1.07
Three-State Average# (92)			
1-hr	1.15 (37)	1.39 (27)	1.24 (28)
6-hr	1.68	1.91	1.63

*Within 1 mile of precipitation station

Values in parentheses are number of stations

#Three-state average computed from total station population rather than average of state averages

Because of the apparent agreement between the results of the study in Arizona data and those previously found for the Tennessee River Basin (that is an increase in average maximum with increasing terrain roughness), a comparable evaluation was made for Nevada and Utah with the results also presented in table 4. There were 33 available stations in Utah and 23 in Nevada. Data for these states do not show a similar trend for increased maximum rainfall with increasing terrain roughness. Neither does an average comprised of all stations in the three states as shown in the last rows of table 4.

Upon inspection of the stations it was believed that a 1-mile radius was too restrictive of the surrounding terrain in the Southwest, therefore unrepresentative. A modification of the terrain criteria was made to include a 10-mile radius for smooth- and a 5-mile radius for rough terrain. Slopes less than 100 feet in 1 mile and greater than or equal to 400 feet in 1 mile were used to define smooth and rough terrains in the modified classification. The analysis was again applied to the three states of Arizona, Utah, and Nevada, with the results shown in table 5.

Table 5

Terrain Roughness* Versus Average of Maximum Recorder Rainfall

	Smooth	Intermediate	Rough
		Arizona (36)	
1-hr	1.24 (4)	1.57 (11)	1.90 (21)
6-hr	2.00	2.22	2.31
		Utah (33)	
1-hr	0.71 (3)	1.03 (10)	0.92 (20)
6-hr	1.01	1.23	1.36
		Nevada (23)	
1-hr	0.63 (2)	1.13 (10)	0.80 (11)
6-hr	0.96	1.43	1.26
		Three-State Average# (92)	
1-hr	0.83 (9)	1.21 (31)	1.40 (52)
6-hr	1.32	1.62	1.77

*Within 5 and 10 miles of precipitation station

Values in parentheses represent number of stations

#Three-state average computed from total station population rather than average of state averages

The modified relationship shown in table 5 offers slight improvement with the exception of Nevada. The most noticeable change is apparent in the three-state averages, where both the 1-hour and 6-hour results support the trend of increased maxima with roughness. This trend, however, is to a large degree due to the strong relationship apparent in the Arizona data.

The conclusions of the above analysis also agree with the observation that of the extreme events listed in table 1, only Ft. Mohave occurred in terrain that does not meet the "rough" criteria of either table 4 or 5.

With partial emphasis toward understanding the terrain associated with some of the extreme events of table 1, Hydrometeorological Branch personnel were flown over the locations of storms at Chiatovich Flat, Palmetto, Campo, Vallecito, Ft. Mohave, and near the site at Globe. From this vantage point it was possible to judge the terrain at all sites to be rugged, Ft. Mohave considerably less than the others. However, believed to be more important was the conclusion that at each of these sites there were no obvious features that would fix these occurrences to these locations over others nearby. Therefore, it was believed that each of these storms was a chance event that could have occurred with equal likelihood at surrounding similarly exposed rugged sites.

It is obvious from both the terrain evaluation and the personal site inspection that great difficulty is encountered in classifying terrain in the Southwest. This difficulty is brought about by the fact that in so many cases prominent terrain features protrude abruptly from an otherwise smooth base. Towns where precipitation recording stations are often located are at the base of such features. In categorizing terrain in these situations, it is not known whether emphasis should be given to the prominent feature or to the smoother terrain. Since this study deals with thunderstorms, it can be argued that, almost without exception, thunderstorms of the PMP caliber form over mountain slopes or rugged terrain (based on the few observed cases). However, only slight displacement (by mean winds) would be necessary to have the resulting rainfall occur over smooth terrain. It is believed that this fact may have contaminated clear-cut relations in the terrain associated with maximum recorder rainfall data, and it may be important in the Ft. Mohave storm.

An alternate analysis of radar echoes relative to terrain is discussed in appendix A to this study. Although the echoes used in comparison with terrain categories are from the usual-intensity thunderstorms, generally less than 0.5 inches per hour, a preference was shown for greater frequency of occurrence in mountainous terrain. Because of the limited amount of data used to make the study and the relatively large unit areas needed for the grid system, the terrain relationship was not believed to be meaningful to the present study.

Terrain elevation. The question of elevation variation of PMP thunderstorm rainfall is a perplexing one, particularly so in the Southwest where a limited amount of data exists, most of which provides little useful information, since stations are commonly at lower elevations.

For warm season short-duration rains, elevation relations are poorly related to rainfall amounts because of the complex interrelationships between available moisture, exposure to mean flow, and distance to moisture source regions Previous work in the thunderstorm portion of the Northwest Report [1] resulted in adoption of a constant thunderstorm potential up to an elevation of 5000 feet above sea level. Examination of the maximum short-duration (6 hour) recorder data (used in the terrain roughness study) plotted against station elevation in figures 20a-c does not conflict with acceptance of 5000 ft as a critical elevation for the Southwest States. The envelopes (dashed lines) of the data in figure 20 suggest a decrease between 4000 and 5000 feet. The 5000-ft level was adopted in the present study above which a decrease in PMP rainfall potential would be expected. The decrease was taken as 5 percent per 1000 feet in accordance with the observed decrease in available precipitable water in a saturated pseudoadiabatic atmosphere.

Additional support for the precipitation-elevation relationship is given in the appendix study of radar echoes.

Terrain control of moisture. When considering the distribution of short-duration thunderstorm PMP, the interaction between terrain and moist air flows must be clarified. Extrapolation from extreme observed rainfall events to the PMP event is based on maximization for moisture. The PMP event requires saturation through the greatest possible depth. In the intermountain Southwest, it is believed that total moisture is composed of a low-level quantity from the south that is influenced by terrain and a high-level quantity coming across the Continental Divide from the Gulf of Mexico.

In the Southwest, the high-level moisture (>10,000 feet) is considered to be uneffected by terrain features. However, the mountains act as both barriers and channels to the flow of low-level moisture from southern moisture sources. During the summer thunderstorm season, the normally weak pressure pattern acts inefficiently in supplying quantities of moisture to the Southwest. Nevertheless, various local intensifications in thermal gradient do occur as suggested by Hales [23] that allow moisture surges to pass into interior regions. It is expected that these intermittent surges of low-level moisture permit accumulations to develop that in combination with upper level moisture and suitable triggering of instability lead to extreme rainfall events. Because of the local nature of these low-level surges and the probable movement to interior regions through mountain valleys, it is believed that only the major mountain barriers effectively control the regional variation of PMP events. For this reason, the ranges of the Sierra Nevada, Wasatch, Mogollon Rim and Rockies are considered to be the major effective barriers in drawing the PMP analysis discussed in the next section.

IV. DEVELOPMENT OF THUNDERSTORM PMP

Introduction. The following section presents the studies leading to short-duration (1-6 hour) summertime thunderstorm PMP for the Southwest. These generalized estimates of PMP are for small drainage basins (up to at least 400 sq. mi. in area).

PMP is defined as the greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year. This is often taken in application to be the magnitude of rainfall over a particular basin which will yield the flood flow of which there is virtually no risk of being exceeded. PMP in this study, although essentially conforming to the definitions given above, is considered as the upper limit of rainfall resulting from extreme thunderstorms. The implication here is that the thunderstorm is considered to produce the controlling precipitation over small drainages in the Southwest. Comparison of the observed short-duration extreme events of the type listed in table 1 with the more widespread convergence rains from tropical moisture surges as discussed in secion II, clearly shows that the intense thunderstorms are prototypes of the PMP storm for small basins (< 500 sq. mi.).

The procedure for development of generalized thunderstorm PMP follows basic procedures used in other parts of the country for non-orographic PMP estimates. Moisture maximization of highest observed rainfalls of record is used to derive what is considered to be the lower limit to PMP for their respective locations. However, a usual step in the development, that is, explicit transposition of extremes within meteorologically homogeneous regions, was not considered in the present study because major mountain barriers may have had an influence on the magnitude or location of the reported values.

A majority of the Southwest is sparsely populated and most of the rainfall observers are located near or around towns or major roadways which in almost all instances are found at the lower elevations and valleys. Since thunderstorms appear to occur more frequently over rugged terrain, it is probable that many extreme thunderstorm events have occurred undetected by the observing network. An example of this is the chance observation made at Chiatovich Flat (see table 1). Without question, many other comparably localized extreme events have not been measured. Those events listed in table 1 have been accepted for this study on the basis of the available information discussed in section II.

In the discussion to follow, the methods used to normalize observed storm amounts for duration and elevation along with adjusting for maximum moisture are given. Details in deriving a mapped analysis of 1-hr, 1-sq mi PMP are also presented that include comparison with previous estimates and supporting data. Another section describes the manner in which PMP to 6-hr durations was obtained. Finally, examples have been included to demonstrate the application of these analyses to basin studies.

1-hr, 1-sq mi PMP estimates

For comparative purposes the extreme values from table 1 have been normalized to a 1-hour duration and a common elevation, and adjusted for maximum seasonal moisture. The derivation of the adjustments are described in the subheadings that follow.

Normalization of observed storm depths to 1-hr duration. The extremes from table 1 are for durations of 40 to 150 minutes. Although differences in these values are large, possibly indicative of regional variations, they are, in part, due to differences in storm duration.

Normalization of these storm amounts to 1-hour duration amounts has been accomplished through the depth-duration relationships shown in figure 21. A discussion of the data for and development of the depth-duration curves is given in a later section on PMP to 6 hours (see page 49). In order to determine from figure 21 the proper curve for use for normalization, it is necessary to locate the observation site on the map of 6- to 1-hr ratios (times 100 to obtain percent) of maximum rainfalls shown in figure 24. Having interpolated a 6- to 1-hr percentage ratio, it is possible to construct a curve at a comparable value on figure 21. Following this curve from the 1-hour value to the duration of the particular observed event indicates the adjustment in percent needed to obtain a 1-hr depth (incremental percentages are read along the ordinate).

In this manner, the individual storm amounts were normalized to the 1-hr values shown in column 2 of table 6. This table also includes the most extreme local storm values observed in California.

Adjustment to 5000-ft elevation. The elevations of observed extremes ranged from near sea level (550 ft) to over 10,000 ft. The variation of PMP with elevation recommended in section III calls for no change up to 5000 ft, and a decrease of 5 percent per 1000 ft for elevations above 5000 ft. This adjustment, in effect, normalizes all observations for elevation. The results are listed in column 3 of table 6.

Table 6

Thunderstorm Rainfall Adjustments

Column		1	2	3	4	5	6	7
Storm Location	Date	Observed Amount (in.)	Col. 1 Normalized to 1-hr amt. (in.)	Col. 2 Adjusted to 5000 ft (in.)	Storm Dewpoint (°F)	Maximum Dewpoint (°F)	Moisture-Maximum Factor	Col. 3 Multiplied by Col. 6 PMP (in.)
Palmetto, Nev.	8-11-90	8.8	8.8	9.5	70 (est)	74	1.22	11.6
Campo, Calif.	8-12-91	11.5	10.4	10.4	72	75	1.16	12.1
Ft. Mohave, Nev.	8-28-98	8	8.4	8.4	72	77	1.28	10.8
Globe, Ariz.	7-29-54	3.5	3.7	3.7	70	78	1.48	5.5
Vallecito, Calif.	7-18-55	7.1	6.8	6.8	68	75	1.41	9.6
Chiatovich, Calif.	7-19-55	8.25	6.9	8.6	70	73	1.16	10.0
Morgan, Utah	8-16-58	6.75*	6.75	6.75	67	75	1.48	10.0
Santa Rita, Ariz.	6-29-59	4.5	4.5	4.5	70	77	1.41	6.3
Elko, Nev.	8-27-70	3.64	3.64	3.64	68	74	1.34	4.9
Encinitas, Calif.	10-12-89	7.58	4.0	4.0	65	72	1.41	5.6
Wrights, Calif.	9-12-18	3.5#	3.5	3.5	62	69	1.41	4.9 (est)
Avalon, Calif.	10-21-41	5.53	3.5	3.5	54	66	1.82	6.4
Newton, Calif.	9-18-59	10.6	6.5	6.5	59	68	1.56	10.1

*Maximum amount of 7 inches is questionable, see p. 8

24-hr amount of 8.75 reduced to 1-hr approximation by subtracting 24-hr amount at a nearby station

Adjustment for maximum moisture. The procedure for maximizing rainfalls for the maximum moisture consistent with the season and the storm location is outlined in section II, page 6. Briefly, the assumptions in this approach to PMP are that the extreme rainfalls divided by their storm moisture give a measure of maximum storm mechanism. This storm mechanism when multiplied by maximum moisture gives an estimate of the upper limit to rainfall. In table 6, columns 4 and 5 list the moisture values in terms of storm and maximum warm season (June-Sept) dew points, respectively.

A study of maximum moisture for the Southwest States has shown that greater accuracy can be obtained by separately considering maximum 12-hr persisting 1000-mb dew points in local storm situations and in the general storm. Seasonal curves of 12-hour persisting dew points representing (1) 100-year return-period values for each month, (2) maximum observed values of record, and (3) 2-year return-period values for each month were plotted and analyzed for Salt Lake City, Phoenix, and Yuma. For the summer months of June to September, these curves suggest that the local storm 1000-mb 12-hour persisting dew points adopted for the Southwest, are 2-3 degrees higher than those of the general storm. The local storm maximum dew points have been used in the present study. Column 6 (table 6) presents the moisture adjustment factor which is multiplied by the adjusted amounts in column 3 to obtain the final adjusted extreme depths given in column 7.

Analysis of generalized PMP. The adjusted 1-hour storm values listed in column 7 of table 6 have been plotted to form the basis for a generalized 1-hr 1-sq mi PMP map. It is obvious from these few widely scattered point values that there remains considerable flexibility in establishing a regional pattern.

Furthermore, only selected extremes are believed to be controlling; that is, they would be drawn for, while others are enveloped in order to obtain a smooth pattern. The Palmetto, Nevada event (table 6), is believed questionable and has not been completely used in the thunderstorm PMP map. The storms considered to control for their location are those at Newton, Avalon, Chiatovich Flat, Campo, Ft. Mohave, and Morgan.

One possible analysis of the maximized values from these stations would be to draw explicitly for the data. However, as has been discussed in the latter part of section II and in section III, it is believed that the effects of underlying terrain and moisture flows are important considerations. Low-level moisture mentioned as necessary for a PMP-type event can only come to these areas from the warm waters of the Gulf of California and it is assumed there is a PMP gradient decreasing with distance away from this source. In addition, the major terrain barriers exert an influence on the moisture flow to the extent of either obstructing or channeling it. In section II it has been discussed that the majority of extreme short-duration events are observed in "quiet" synoptic weather situations when strong pressure gradients and moisture inflow are absent. However, this is not to say that a transport of moisture has not occurred nor that an accumulation of moisture with time cannot take place. Thus, it has been assumed that the major terrain barriers represent general controlling factors to overall moisture availability and that they should be included in an analysis of PMP.

A preliminary 1-hour, 1-sq mi PMP map was drawn from the controlling maximized values and considering the assumptions of moisture and terrain control mentioned above. The resulting analysis supersedes earlier tentative estimates prepared by the Hydrometeorological Branch in 1968 [2a].

Supportive data analysis. Support for the preceding analysis was given by an investigation of extreme data for hourly recorder stations. Considered the best support are the maximum 1-hour amounts satisfying the conditions listed in table 7 (see page 58). These data, including the extreme events at Elko, Nevada, and Santa Rita, Arizona, were analyzed for rainfall at one-half inch intervals as shown in figure 22.

The predominant features in figure 22 are the three zones of maximum rainfall protruding northward from the southern border. Taken in the sense of low-level moisture interacting with terrain controls, they show a narrow tongue of rainfall maxima along and to the east of the ridge of coastal mountains from southern California toward the San Francisco Bay area and with lowest values along the coast. A maximum begins again north of the Bay area and broadens to include most of northern California. A second broad zone of high values is shown to penetrate northwestward toward the Salt Lake Basin. The third zone of maximum rainfalls extends from central New Mexico to central Utah. Significant areas of smallest 1-hour maximums occur in the San Joaquin Valley, the Owens Valley - Death Valley area, the high plateau mountains of Nevada and western Colorado, and a zone in northeastern Arizona.

Also noted in figure 22 are other isolated maxima that appear considerably larger than the analysis supports based upon surrounding data. Elko is an example, and although in most instances the analysis was not drawn specifically to these amounts, it was drawn such that these maximum amounts occurred within zones of maxima.

The analysis of data in figure 22 to a large extent reflects terrain control on low-level moisture. Evidence is noted along the Coast Range in southern California of what may be the result of forced convergence on moist airflows by narrowing valleys. Such convergence could explain the extreme of 7.1 inches at Vallecito, Calif (table 6) and the relatively high recorder rainfalls noted at the heads of moisture-directed valleys such as the 2.19-in. amount at Crawford Ranch and the 2.58-in. amount at Julian, both near the head of Vallecito Valley, and the 2.10-in. amount at Beaumont near the base of 11,500-ft Mt. Gorgonio where the San Bernadino and San Jacinto Mountain ridges converge. Other lesser examples of possible convergence effects are noted along the southern slopes of the mountains in Arizona.

Adopted 1-hr PMP map. In comparing the maximum 1-hour analysis from figure 22 with the PMP analysis drawn from adjusted extreme data, many features of agreement appeared in pattern shape. It was because of this comparison that some additional modifications were made to the PMP map to conform to tendancies of the maximum recorder rainfall 1-hour map where such changes did not oppose the extreme data.

Figure 23 presents the 1-hr, 1-sq mi PMP (also drawn at 1:2,000,000 scale) analysis that has been adopted in the present study. Isohyets are shown at intervals of 1 inch with supplemental half-inch isohyets indicated in some portions for clarification. In addition, locations of maximum and minimum PMP amounts has been added for ease in interpolation.

The dominant feature in figure 23 is the area of maximum PMP extending from the Coastal Mountains over the Imperial Valley of southern California. A narrow extension of this maximum continues up the Coastal Range with minimum values again along the coast. In northern California, a small area of maximum has been drawn to include the observed moisture-maximized amounts at Newton and Kennet north of Redding. The position of this maximum conforms to an area of high values at the northern end of the Sacramento Valley. The largest area of maximums occurs through the middle of the Southwest States. This broad tongue has PMP values ranging from over 11.5 inches in southwest Arizona to near 8 inches along the Nevada-Oregon border. An arm of 10-inch PMP extends northeastward to include Morgan and agrees with a similar feature shown on the analysis of maximum 1-hr recorder values, figure 22. The maximum 1-hour analysis had an influence in the PMP analysis particularly in northern Nevada. The fact that this area is a minimum in figure 22 has resulted in restricting the PMP amounts in figure 23, whereas another possible analysis might be to loop the 10-inch isohyet from Morgan across northern Nevada and then southward east of Chiatovich Flat. The latter analysis would raise the PMP estimate by nearly two inches from that shown in figure 22 and is not believed to be as justified as the indicated pattern.

Also shown in figure 23 is a large area of minimum PMP extending from the Mogollon ridge through northeastern Arizona and northeastward to western Colorado. Two cells of minimum PMP of about 7.5 inches are separated by a moderate maximum of about 8.3 inches. These configurations conform, in general, with the pattern of maximum recorder 1-hr data (figure 22).

The area of lowest PMP values occurs in the Central Valley of California supported by both the maximum 1-hour analysis and the knowledge that warm-season thunderstorms are extremely rare (almost non-existent for depths > 0.2 inch) through this region.

The broad-scale agreement between the PMP analysis and the maximum 1-hour data analysis is good in most instances. Small-scale features in the recorder data map (figure 22) are not likely to appear in the broad-scale pattern suggested by figure 23. It is expected also that the isohyetal gradients in the PMP analysis are less than those shown by the maximum 1-hour recorder data and that the PMP analysis smooths over many minor details of the recorder maxima that are due to chance occurrences within the relatively short period of record.

It is of interest to note that the pattern of generalized PMP shown in figure 23 approximates the shape of the maximum moisture charts for July and August [4]. Lowest maximum persisting 12-hour dew points occur along the Pacific coast with a push of maximum-moisture values northward through Arizona and a tendency for relatively lower values in northern New Mexico and western Colorado. Because July and August are the middle months of the warm season thunderstorms in the Southwest, it is believed that the moisture charts are additional support for the 1-hr PMP map, figure 23.

In summarizing the short-duration thunderstorm PMP estimates represented in figure 23, it is shown that maximum values occur along a broad swath passing northward through the center of the Southwest States. To east and west of this zone of maxima lie zones of lesser PMP caused to a large extent by the moisture-controlling effects of the major terrain barriers in these areas. The estimates proposed in figure 23, particularly on the eastern flank, are tentative and subject to further adjustment pending continued study of thunderstorm PMP along the eastern slopes of the Rocky Mountains.

Extension of PMP to 6 hours

Discussion. Although it is evident from the list of extreme rainfalls in table 1 that no storm lasted longer than about three hours, in the most extreme or PMP storm, it is postulated that the storm could last for 6 hours. A large percentage of the total storm should occur in the first hour and essentially all within 3 hours. The exception lies in the coastal drainage areas of California where a more continuous inflow of moisture is possible. Lesser storms of the type described by the Queen Creek, Arizona, event have lasted considerably longer. This storm left 5.3 inches in a 6.5-hour period during the early morning hours of August 19, 1954 [31]. The Queen Creek storm appears to be typical of surges of moist tropical air northward from the Gulf of California. Thus, in contrast to earlier comments that 1-hr thunderstorm extremes are typified by a quiet synoptic sitation, the 6-hr extreme storm probably requires some indirect association with a general-type pattern.

Although it is indirectly possible to develop a depth-duration relationship from the few actual extreme data, an alternate approach was devised based on more frequent, but lesser thunderstorm rainfalls observed at recorder stations. The following sections describe the data used to shape and obtain the variable relationships already presented in figure 21. From these data it has been possible to make an analysis of 6- to 1-hr ratios which are used to extend the 1-hour PMP to the 6-hour storm.

Generalized shape of depth-duration curve. The general shape of the basic depth-duration curve for PMP is based on selected highest recorded summer 6-hour storm rainfalls in the intermountain region and comparisons with storm depth-duration relations in other regions.

Table 8 compares the data used in this study. Depth-duration curves were made for each of the 17 greatest 3-hour rains from summer storms for Utah, Nevada, and Arizona [32, 33]. The average of these individual curves, in percent of the 1-hour amount, is given on line 1 of table 8. A comparable average relationship was determined from curves representing 14 of the most extreme short-duration storms listed in "Storm Rainfall" [34] and shown on line 2 of the table.

While the 3-hour rains for the intermountain region storms averaged 1.6 inches, the 3-hour rains of the 14 storms from the Eastern and Central States averaged 9.4 inches and ranged between 5 and 22 inches.

One of the best-documented thunderstorm rainfalls of record for the Southwest occurred March 3, 1943, in Los Angeles County, California [35]. The 3-hour rain (total duration) was 3.3 inches. Even though this storm was imbedded in more general rains covering parts of several states during March 3-6, the large amount of reliable data for the event make it useful for thunderstorm depth-duration realtionships in this area. Table 8 shows the Los Angeles County thunderstorm curve to be quite similar to those of the other analyses.

The last line of table 8 presents the general depth-duration relation adopted for the PMP thunderstorm in the Northwest report [1]. This relationship was developed from consideration of moisture maximized and transposed storms which set the enveloping depth-duration curves for short durations. It is apparent that the curve given by line 4 is, in general, representative of the three other curves given in table 8 and it was this curve that was taken to provide the basic shape of the depth-duration relationship adopted for the Southwest and is shown as the dashed line in figure 21.

Table 8

General Depth-Duration Relation for Thunderstorm PMP

	Duration (hr)			
	1	2	3	6
	Percent 1-hr values			
1. Average of 17 storms Utah, Nevada, and Arizona (recorder data)	100	125	133	152
2. Average of 14 most extreme short-duration storms in Storm Rainfall [34]	100	125	135	166
3. March 3, 1943, Los Angeles storm	100	118	128	--
4. Relation adopted for Northwest report	100	119	129	144

Durational variability. Because storms of PMP potential draw moisture from areas many times larger than the storm itself, direct and continuous resupply is necessary as duration increases. Therefore, decreasing 6-hour amounts are to be expected with increasing distance from moisture sources. For the Southwest the most important sources of direct moisture resupply are the Gulf of California and the Pacific Ocean.

It was also because of the need for continuous moisture inflow that the effect of terrain barriers on low-level flow is believed to be of greater importance for 6 hours than for the 1-hour PMP. A study was made of maximum 1- and 6-hour rainfalls at recorder stations in order to support the conclusions on terrain effect and moisture sources for the 6-hour PMP storm.

The approach taken was to plot the 6- to 1-hour ratio of maximum rainfalls satisfying a particular set of conditions as outlined on page 58. Tabulated maximum 1-, 6-, and 24-hour rainfalls for each month of record at each station were made available by the Special Studies Branch, Office of Hydrology, for a period of record of approximately 30 years.

The 1- and 6-hour amounts satisfying the conditions of table 7 were listed for each recording station. The 6- and 1-hour ratios were computed and averaged by station. The station averaged ratios were plotted and a smoothed analysis drawn from the data.

From the wide range of 6- to 1-hr ratios obtained for the Southwest, it became apparent that a single depth-duration relationship was not acceptable to the entire area. In order to devise a variable relationship, it was decided to establish a family of curves whose 6-hr values were increments of 10 percent greater than the 1-hr PMP amount. Further simplification was obtained by presenting all relationships in terms of the 1-hr PMP.

The family of curves were obtained by first drawing a smooth curve between the 1-hr PMP (100 percent) and the 6-hr PMP (110 percent of the 1-hr PMP), based on a reasonable extension of the existing curve from 0 to 1 hour. The remaining curves were determined by ratioing their 6-hr values against the differences between 110 percent and the dashed curve shown in figure 21.

<u>6- to 1-hr rain ratio analysis.</u> The initial study of plotted, station-averaged 6- to 1-hr ratios revealed a wide range of values, from about 1.1 in eastern Utah to over 2.8 along the California coast. An analysis was made of these values which both fit the data and supported the expected sheltering effect of major terrain barriers. Concern developed, however, as to whether the resulting analysis was a representative assessment of 6-hr PMP conditions. Without the benefit of observational information, it

was believed that 6- to 1-hr PMP ratios are likely to be less than those determined from maximum hourly observed rain data. The prime reason for this conclusion was the opinion that a continuous supply of maximum moisture to the PMP storm is improbable. This reasoning is, in turn,based upon the fact that most observed extreme thunderstorms in the Southwest are less than 3 hours duration.

The technique applied to reduce the initial 6- to 1-hr station values was that of smoothing, best accomplished by grid averaging. Grid units of 2° longitude by 2° latitude were created for the entire Southwest within which averages were obtained of the 6- to 1-hr station values. The new grid unit averages were assumed to represent the entire square without further consideration for terrain or number of stations.

Isolines of 6- to 1-hr ratios to be used for PMP were drawn for these doubly-smoothed grid values as shown in figure 24. It was apparent that with only slight adjustment the resulting analysis reflected the influence of major terrain barriers. Especially so is the strong gradient that occurs along the eastern slope of the Sierra Nevada. Figure 24 shows a broad area of low ratios (120-140%) to the east of the Sierra Nevada. Within this area is a zone of minimum ratios (110-120%), centered in the plateau region of northeastern Arizona and eastern Utah. This minimum is believed caused by the sheltering effects of the Wasatch range on the west, the Mogollon Rim to the south, and the Rockies to the east. An apparent minimum occurs in Nevada. This feature is, however, questionable in that there are no broadscale topographic features and few stations supporting it. It is expected that if additional stations had been available, ratios closer to 130-140 percent would have occurred in this area.

Although it is difficult to judge the accuracy of data through mountainous areas, the averages across the Rocky Mountains provided in figure 24 suggest a slight increase in ratios to the east of the Divide.

With the exception of the Mojave Desert, the analysis in California shows considerably greater ratios. The maximum along the coast and into the Upper Central and Sacramento Valleys exceeds 180 percent, and the gradient reflects the effects of the most prominent terrain features.

Having adopted the distribution of 6- to 1-hr ratios shown in figure 24, it is now possible to determine PMP estimates for any incremental duration up to 6 hours with the aid of figure 21. One-hour estimates for locations in the Southwest are obtained directly from figure 23. For longer durations, locate the basin center on figure 24 and interpolate the ratio at that point. Use the latter ratio in figure 21 to determine the appropriate depth-duration relationship.

PMP for durations less than 1 hour

Since many basins in the Southwest for which PMP is required are small and have short concentration times, it is useful to include information on durations less than one hour. For a period of record between 1954 and 1970, cases of excessive precipitation [48] at first-order stations in Utah, Arizona, Nevada, and southern California were examined. The results of these evaluations support the conclusion that for storms with low 6- to 1-hr ratios the 15-minute rainfall is proportionately greater than for storms with high 6- to 1-hr ratios. Geographical distribution of highest 15-minute to 1-hr rain ratios agree well with the 6- to 1-hr ratios of figure 24. For example, Los Angeles and San Diego (high 6- to 1-hr ratios) have low

15-minute to 1-hr ratios (approximately 0.60) whereas the 15-minute to 1-hr ratios in Arizona and Utah (low 6- to 1-hr ratios) are generally higher (approximately 0.75).

The depth-duration relations for durations from 15 minutes to 6 hours were combined and presented on figure 21. A small adjustment has been made to some of the curves at durations greater than one hour to provide smoother relationships through the common point at one hour. It is also believed justified to reduce the number of curves shown at durations less than one hour and let a single short-duration curve apply to a range of 6- to 1-hr duration curves. The corresponding curves have been indicated by letter designators, A-D, shown on figure 21.

Depth-area variation.

Extreme summer thunderstorm rainfall for the Southwest has been taken to represent PMP over an area of 1 square mile. When applying PMP to a specific basin, an important consideration is how 1-sq mi PMP should decrease with increasing area. A method for developing depth-area variations was discussed in the Northwest report [1] and was based upon a study of (a) eastern-type thunderstorms, (b) intense thunderstorms observed west of the Continental Divide, and (c) model thunderstorms. Depth-area data for the storms in (a) and (b) were plotted and curves were drawn to indicate 1-, 3-, and 6-hr durational relationships.

The resulting curves from the Northwest report were used as a basis for relations for the Southwest. Slight modifications were made, however particularly to eliminate the tendency toward convergence of the duration curves exhibited at large areas (>300 sq mi). By making the duration curves parallel, the unrealistic results brought about by convergence disappeared.

Figure 26 shows the depth-area relationships adopted for the Southwest. Additional duration curves have been included for clarification and reduction of extrapolation in application. Basin areas up to 500 square miles and durations up to 6 hours can be found in figure 26 to yield basin-averaged PMP in percent of the 1-sq mi PMP. Durations under 1 hr limited to areas < 200 sq mi.

The consideration for model thunderstorm analysis listed in (c) above and used in the Northwest report has been modified also for the Southwest. An elliptical isohyetal pattern was believed to be more representative of the few available extreme rainfall patterns than were circular isohyets. The extreme storms at Globe and Vallecito were examples from which an isohyetal pattern having a 2:1 axial ratio was adopted for general application throughout the Southwest (see typical pattern in figure 27).

Time distribution of incremental PMP

Very little information is available upon which the sequence of incremental rainfall can be established. A study of successive time increments in each of 38 six-hr storms resulted in an average mass curve in which the maximum intensities occurred in the middle of the storm period [36]. The distribution of incremental PMP for the Southwest 6-hr thunderstorm in accord with the results of the above study is presented in column 2 of table 11a. A small variation from this distribution has been noted in the time sequence of hourly increments for a 6-hr storm presented in Engineering Manual 1110-2-1411 [37]. The latter is listed in column 3 of table 11a, and places emphasis of maximum incremental amounts more toward the end of the period. In application, the choice of either of these distributions is left to user since one may prove to be more critical in a specific case than the other.

An investigation was made into the distribution of 15-minute rain increments in a 1-hr storm. Ten years of excessive precipitation data for summertime at first-order stations in the Southwest were used to determine 15-minute amounts. Eighty-two percent (27 of 33 cases) of the events suggested that the greatest intensity occurred in the first 15-minute interval. HMR No. 5 [36] supports this conclusion although based on data from a broad geographical coverage of storms. It is stated in that report that this distribution is a well-known characteristic of point rainfall in a thunderstorm. Additional support for acceptance of this time distribution is found in the reports of specific storms by Keppell [49] and Osborn and Renard [43]. From all these sources it has been concluded that the most representative time sequence of 15-minute incremental rainfall is that given in table 11b.

Seasonal distribution of PMP

Information was requested regarding the period of the year when thunderstorm PMP was most likely. Guidance was obtained from a study of the distribution of maximum thunderstorm events through the warm season at each of the recording stations in Utah, Arizona, and in southern California (south of 37°N and east of the ridgeline). The period of record used for this study was between 1940 and 1970, averaging 27 years. Since isolated thunderstorm rainfalls rarely occur during the summer months along the coastal drainage basins of California, this region was not included. The month in which the one greatest thunderstorm rainfall for the period of record at each station (according to the definition given in table 7) was noted. The seasonal distribution for each state is given in table 9.

Table 9

Distribution of Maximum Thunderstorm Rainfalls

	Month						
	M	J	J	A	S	O	No. of Cases
Utah	1	5	9	14	5		34
Arizona		4	16	19	4		43
So. Calif.*		14	10	7			31

*South of 37°N and east of ridgeline

In general, the information in table 9 agrees well with the months of occurrence of the extreme thunderstorm rainfalls for the Southwest listed in table 1. July and August represent the months of maximum likelihood for the major portion of Arizona, Utah, Nevada, and southeastern California, as shown on figure 25a. The influence of a slightly earlier monthly period of maximum, determined in the Northwest Report [1], appears for stations in northeastern Nevada and northwestern Utah.

For the coastal drainages of California most thunderstorms are associated with general storm rainfalls (see discussion on pages 28-32a). The occurrence of these cool-season mid-latitude and tropical storm systems is limited to the spring and fall months as indicated in the events listed in table 3. Figure 25a presents the regional variation of months when there is the greatest potential for a thunderstorm event approaching the magnitude of PMP.

Table 7

Conditions Set for Selection of Storms for Determining 6- to 1-Hour Ratios

1. Use only storms in summer months of May to September.
2. Extract data indicative of 6-hour storms; i.e., the dates of 1-, 6-, and 24-hour rainfall amounts must be the same and the 24-hour value must not exceed the 6-hour value by more than 0.1 inch.*
3. Consider only the larger storms of record. Minimum 1-hour criteria were determined such that ratios were obtained for nearly all recording stations. These criteria varied over the Southwest as shown by figure 25. The adequacy of the boundaries selected is supported by the fact that few discontinuities in ratios occurred across the boundaries. Minimums for considered 1-hour rainfalls were based on the following criteria.

Idaho, Wyoming, Colorado, Utah	>0.5 inch
Nevada	>0.5 in., except southeast tip >1.0 in.
Arizona	>1.0 in., except northern border >0.5 in.
New Mexico	>1.0 in., except northwest corner >0.5 in.
California	>0.5 in., except Central Valley and Pacific Coast >0.2 in.

*The criteria were established to separate storms of 6 hours or less total duration from the more general type storms.

Table 7

Conditions Set for Selection of Storms for Determining 6- to 1-Hour Ratios

1. Use only storms in summer months of May to September.

2. Extract data suggestive of 6-hour storms, i.e., the dates of 1-, 6-, and 24-hour rainfall amounts must be the same and the 24-hour value must not exceed the 6-hour value by more than 0.1 inch.*

3. Consider only the larger storms of record. Minimum 1-hour criteria were determined such that ratios were obtained for nearly all recording stations. These criteria varied over the Southwest as shown by Figure 13. The adequacy of the boundaries selected is supported by the fact that few discontinuities in ratios occurred across the boundaries. Minimums for considered 1-hour rainfalls were based on the following analysis.

Idaho
Wyoming
Colorado
Utah

$\geq$0.5 in.

Nevada $\geq$0.5 in., except southeast tip $\geq$1.0 in.

Arizona $\geq$1.0 in., except northern border $\geq$0.5 in.

New Mexico $\geq$1.0 in., except northwest corner $\geq$0.5 in.

California $\geq$0.5 in., except Central Valley and Pacific Coast $\geq$0.2 in.

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*The criteria were established to separate storms of 6 hours or [illegible] [illegible] duration from the more general type storms.

V. PROCEDURES FOR OBTAINING BASIN THUNDERSTORM PMP VALUES

The previous sections describe the development of thunderstorm PMP for the Southwest. The end products of this study are essentially the two charts presented as figures 23 and 24. It has been apparent from the generalized approach considered in developing these results that with regard to field applications there may be instances where problems may occur. In each application, it will be necessary to make a preliminary judgment to relate a specific basin to its surroundings, particularly if it lies in mountainous terrain and is in a portion of the charts where PMP isolines are more closely spaced. In these cases, it is anticipated that some difficulty will develop in interpolating a representative value. As guidance, it is suggested that knowledge of the basin exposure is the best lead to a proper selection.

In an effort to further clarify the application of this study to field determination, the present section offers step-by-step procedures for computing basin average and areal distribution of PMP over a basin. Examples of each have been included.

<u>Basin average thunderstorm PMP</u>

Basin average depths are readily obtained by the following method.*

<u>Step</u>

1. Fix the location of the basin for which thunderstorm PMP is required on figure 23 and read an interpolated value for 1-hr, 1-sq mi PMP, in inches.

---

*If the areal distribution of PMP is required, see discussion on page 63.

2. If the lowest elevation within the basin is above 5000 ft, decrease the PMP value from step 1 by 5 percent for each 1000 ft above 5000 ft or proportionate fraction.

3. Use figure 24 to find the appropriate 6- to 1-hr ratio for the basin location.

4. Enter table 10 at the ratio from step 3 to obtain percentage durational variations and multiply each of these percentages by the 1-hr PMP from step 1 (step 2, if applicable).

5. Enter the abscissa of figure 26 with the size of the basin area to obtain the areal reduction at corresponding durations in terms of percent of 1-sq mi PMP . For durations less than one hour, areal reduction is applicable only to basins less than 200 square miles.

6. Multiply the areal reduction percentages from step 5 by the respective PMP values from step 4.

7. Determine the incremental values of the hourly PMP values found in step 6 by subtracting each hourly value from the following hourly value.

8. Arrange the incremental values from step 7 in one of the time sequences shown in table 11a for a 6-hr storm. **Use the sequence of table 11b for increments of 1-hour PMP.**

Table 10

Durational Variation of 1-sq mi PMP
(percent of 1-hr PMP)

6-/1-hr ratio	Duration (hr)							
	1/4	1/2	1	2	3	4	5	6
1.1	86	93	100	107	109	110	110	110
1.2	74	89	100	110	115	118	119	120
1.3	74	89	100	114	121	125	128	130
1.4	63	83	100	118	126	132	137	140
1.5	63	83	100	121	132	140	145	150
1.6	43	70	100	124	138	147	154	160
1.8	43	70	100	130	149	161	171	180
2.0	43	70	100	137	161	175	188	200

Table 11

a. Time Sequence for Hourly Incremental PMP

Increment	Sequence Position	
	HMR #5	EM 1110-2-1411
Largest hourly amt	Third	Fourth
2nd largest	Fourth	Third
3rd largest	Second	Fifth
4th largest	Fifth	Second
5th largest	First	Last
Least	Last	First

b. Time sequence for 15-Minute Incremental PMP for storms less than 1 Hour

Increment	Sequence Position
	(1-hr storms)
Largest 15-min amt.	First
2nd largest	Second
3rd largest	Third
Least	Last

EXAMPLE:

To find the basin average 6-hr summer PMP thunderstorm, given that:

Basin area is 410 sq mi.

Minimum basin elevation is 4200 ft.

Basin location indicates that 1-hr 1-sq mi PMP is 11.0 inches and that the 6- to 1-hr ratio is 1.5.

Following the procedures outlined above gives:

Step

1, 2, and 3. Information regarding basin area, elevation, 1-hr 1-sq mi PMP, and 6- to 1-hr ratio has been given above, which otherwise would be obtained from figures 23 and 24.

4. From table 10 for a ratio of 1.5, obtain the following depths, in percent of the 1-hr 1-sq mi PMP, and multiply by the 1-hr PMP, 11.0 in.

	Duration (hr)							
	1/4	1/2	1	2	3	4	5	6
(%)	63	83	100	121	132	140	145	150
(in)	6.9	9.1	11.0	13.3	14.5	15.4	16.0	16.5

5. No reduction is made for durations less than one hour for this size basin. Areal reduction from figure 26 for a basin of 410 sq mi gives:

	Duration (hr)					
	1	2	3	4	5	6
(%)	24	28	32	34	36	38

6. Areally reduced PMP in inches computed by multiplying values of step 5 by those of step 4.

	Duration (hr)					
	1	2	3	4	5	6
(in)	2.6	3.7	4.6	5.2	5.8	6.3

EXAMPLE--Continued

7. Hourly incremental PMP.

	1st	2nd	3rd	4th	5th	6th
(in.)	2.6	1.1	.9	.6	.6	.5

8. Time sequence of PMP increments arranged according to HMR No. 5 in table 11.

	1	2	3	4	5	6
(in.)	.6	.9	2.6	1.1	.6	.5

Areal distribution of PMP over a basin (incremental isohyetal labels)

For small drainages, the average depths of PMP obtained by the preceding steps will usually be satisfactory for computing the flood hydrograph. Areal distribution of PMP depths is needed in many cases for larger drainages and some smaller drainages depending on hydrologic characteristics and the degree of uniformity of the drainage. An elliptical shaped isohyetal pattern having a major axis twice the minor axis has been adopted for distributing thunderstorm PMP in the Southwest States. This, in part, reflects the observed patterns of the Globe, Ariz., and Vallecito, Calif. storms presented in section II. The pattern is shown in figure 27. Individual isohyets are labeled alphabetically and the area contained within each is indicated. In application, it is stressed that the scale of the basin diagram agree with that of the isohyetal pattern.

Table 12a presents labels for durations less than 1 hour in terms of percent of the 1-hr, 1-sq mi PMP for the set of isohyets shown in figure 27. The four sets of data presented in table 12a satisfy the individual durational relationships for short duration 6-/1-hr ratio curves A-D shown in figure 21 (see letter designators). No isohyetal labels are given for areas larger than 200 square miles at durations less than one hour.

Table 12a

Isohyetal Labels in Percent of 1-Hr, 1-Sq Mi PMP
(15-, 30-, and 60-minute PMP)

	Isohyets	A	B	C	D	E	F	G	H	I	J
		Enclosed Areas (sq mi)									
	Duration (min)	1	5	25	55	95	150	220	300	385	500
A	60	100	82	58	44	32	23	16	13	12	11
	30	93	71	45	32	22	15				
	15	86	62	37	24						
B	60	100	82	58	44	32	23	16	13	12	11
	30	89	68	43	30	21	14				
	15	74	53	31	20						
C	60	100	82	58	44	32	23	16	13	12	11
	30	83	63	40	28	19	13				
	15	63	45	27	17						
D	60	100	82	58	44	32	23	16	13	12	11
	30	70	53	35	24	16	9				
	15	43	31	18	12						

6-/1-hr ratio index (see figure 21)

Table 12b

Isohyetal Labels in Percent of 1-Hr, 1-Sq Mi PMP
(2nd to 6th hour incremental PMP)

6-/1-hr Ratio	A	B	C	D	E	F	G	H	I	J
	2nd Highest 1-hr Increment									
110	8	8	8	8	8	7	6	4	4	4
120	11	11	11	11	10	8	7	5	5	5
130	14	14	14	12	11	9	7	5	5	5
140	17	17	16	14	12	10	8	6	6	6
150	21	20	18	16	13	11	8	6	6	6
160	24	23	20	18	15	12	9	7	7	6
170	27	26	23	20	16	13	10	7	7	7
180	30	29	25	21	17	14	10	8	8	7
190	34	32	27	23	18	14	11	8	8	8

Table 12b - Continued

Isohyetal Labels in Percent of 1-Hr, 1-Sq Mi PMP

6-/1-hr Ratio	Isohyets A	B	C	D	E	F	G	H	I	J
				3rd Highest 1-hr Increment						
110	2	2	2	2	2	2	2	2	2	2
120	4	4	4	4	4	4	4	4	4	4
130	6	6	6	6	6	6	5	4	4	4
140	9	9	9	9	8	7	6	5	5	5
150	11	11	11	11	10	8	7	5	5	5
160	14	14	14	13	11	10	8	6	6	6
170	17	17	17	14	13	11	8	7	6	6
180	19	19	18	16	14	12	9	7	6	6
190	21	21	20	18	15	13	10	8	7	7
				4th Highest 1-hr Increment						
110	0	0	0	0	0	0	0	0	0	0
120	2	2	2	2	2	2	2	2	2	2
130	4	4	4	4	4	4	4	3	3	3
140	6	6	6	6	6	5	4	4	4	4
150	7	7	7	7	7	6	5	4	4	4
160	8	8	8	8	7	6	5	5	5	5
170	10	10	10	9	8	7	6	5	5	5
180	12	11	11	10	9	8	7	6	5	5
190	14	13	12	11	10	9	7	6	6	6
				5th Highest 1-hr Increment						
110	0	0	0	0	0	0	0	0	0	0
120	1	1	1	1	1	1	1	1	1	1
130	3	3	3	3	3	3	3	3	3	3
140	5	5	5	5	5	5	4	4	4	4
150	6	6	6	6	6	5	5	4	4	4
160	7	7	7	7	7	6	5	5	5	5
170	9	9	9	9	8	7	5	5	5	5
180	10	10	10	10	9	7	6	6	5	5
190	12	12	12	11	9	8	6	6	6	6
				6th Highest 1-hr Increment						
110- 120	0	0	0	0	0	0	0	0	0	0
130	2	2	2	2	2	2	2	2	2	2
140	4	4	4	4	4	4	4	4	4	3
150	5	5	5	5	5	5	4	4	4	4
160	6	6	6	6	6	5	5	5	5	5
170	7	7	7	7	7	6	5	5	5	5
180	8	8	8	8	8	6	5	5	5	5
190	9	9	9	9	8	7	6	6	5	5

Table 12b presents isohyetal labels for PMP increments other than the highest 1-hr value relative to the various 6-/1-hr ratio relationships shown in figure 21. The 2d increment represents the 2d highest 1-hr PMP, and so on. It should be noted that linear interpolation may be used to obtain labels for ratios intermediate to those presented. Application of these tables will be demonstrated through an example following the procedure for determining areal distribution of PMP. Once derived they can be arranged in one of the time sequences given in table 11.

The following steps are recommended for obtaining the areal distribution of PMP within a basin if required.

<u>Step</u>

1. Place a tracing of the isohyetal pattern from figure 27 (adjusted to the same map scale) over the basin and rotate to obtain the maximum precipitation volume in the basin.
2. Note the isohyets that cover the basin for which labels are required.
3. Locate the basin center on figure 23 and determine the 1-hr, 1-sq mi PMP value in inches.
4. If the lowest elevation within the basin is above 5000 ft, decrease the PMP value from step 3 by 5 percent for each 1000 ft above 5000 ft, or proportionate fraction.
5. Use figure 24 to find the appropriate 6- to 1-hr ratio for the basin.
6. Use table 12a to obtain isohyetal labels for durations up to and including one hour in percent of 1-hr, 1-sq mi PMP.

7. Obtain isohyetal labels for the 2d highest to 6th highest (the lowest) 1-hr incremental PMP values in percent of 1-hr, 1-sq mi PMP from table 12b.

8. Multiply the isohyetal percentages for each hourly increment from step 6 and 7 by the 1-hr, 1-sq mi PMP value from step 3 (step 4, if applicable). These values are incremental isohyetal PMP labels in inches, and can be arranged in a time sequence according to table 11, if required.

EXAMPLE:

To find incremental isohyetal labels for a 6-hr summer PMP thunderstorm, given that:

Basin area is 410 sq mi

Minimum basin elevation is 4200 ft

For the basin location, the 1-hr, 1-sq mi PMP is 11.0 inches, and the 6- to 1-hr ratio is 1.5.

Following the steps just outlined results in the step-by-step determination below. For this example it is assumed that 15-min and 30-min PMP are not required.

<u>Step</u>

1. Superimpose the prototype isohyetal pattern from figure 27 over the basin shape drawn to matching scales as shown for this example in figure 28.

2. In this example it is necessary to determine labels for all isohyets, A-J.

3-5. Information regarding basin area, 1-hr, 1-sq mi PMP (step 3) elevation (step 4), and 6- to 1-hr ratios (step 5) has been given above which otherwise would be obtained from use of figures 23 and 24.

6-7. From table 12a obtain isohyetal labels for 1-hr PMP in percent of the 1-sq mi value. From table 12b obtain the remaining incremental isohyetal labels in percent of 1-hr, 1-sq mi PMP. Combine these percentages to form a table as shown below.

EXAMPLE

Isohyetal Labels in Percent of 1-hr, 1-sq mi PMP

	(highest)	Highest 1-hr Increments				(lowest)
Label	1st	2nd	3rd	4th	5th	6th
A	100	21	11	7	6	5
B	82	20	11	7	6	5
C	58	18	11	7	6	5
D	44	16	11	7	6	5
E	32	13	10	7	6	5
F	23	11	8	6	5	5
G	16	8	7	5	5	4
H	13	6	5	4	4	4
I	12	6	5	4	4	4
J	11	6	5	4	4	4

8. Conversion of the above labels to PMP is accomplished by multiplying the values of step 7 by the 1-hr, 1-sq mi PMP to get isohyetal labels in inches; see following table.
Note that an average depth equal to the values of the last isohyet (J) may be assumed for the portion of the basin not covered by the isohyetal pattern.

EXAMPLE

Incremental Isohyet Labels (in.)

Label	(highest) 1st	Highest 1-hr Increments 2nd	3rd	4th	5th	(lowest) 6th
A	11.0	2.3	1.2	.8	.7	.6
B	9.0	2.2	1.2	.8	.7	.6
C	6.4	2.0	1.2	.8	.7	.6
D	4.8	1.8	1.2	.8	.7	.6
E	3.5	1.4	1.1	.8	.7	.6
F	2.5	1.2	.9	.7	.6	.6
G	1.8	.9	.8	.6	.6	.4
H	1.4	.7	.6	.4	.4	.4
I	1.3	.7	.6	.4	.4	.4
J	1.2	.7	.6	.4	.4	.4

APPENDIX A

Pilot Study of Radar Echoes

Introduction. The fact that almost all major intense short-duration thunderstorm rainfalls have occurred over "rough" terrain (section III) suggests there is an association between cumulus development and terrain roughness. References supporting such an association are found in the literature. Namias, for example, states [38], "... practically all types of thunderstorms are more frequent over hilly and particularly over mountainous country than flat terrain." Reasons given for this preference are the effects of orographic upthrusting in cases of low-level moist air flows, or the effects of intense thermal insolation which shows a preference for higher elevations and properly oriented slopes.

The complex terrain of the southwest along with the distribution of precipitation stations being biased toward lower elevations makes it difficult to detect consistent relationships of hourly rainfall data with terrain features. Nevertheless, interest in delineating preferred regions for thunderstorm development has led to a search for alternate methods of analyzing the effects of terrain. One such approach was to consider the distribution of radar echoes.

Although radar coverage is poor in the intermountain west compared to that east of the Rockies, an attempt was made to establish terrain-echo relationships. One aspect was an attempt to correlate radar-echo occurrence with roughness of terrain, where terrain was categorized as smooth, intermediate, and rough. Another was a comparison of radar-echo count with terrain elevation. The studies were based on a limited amount of readily available data.

Data

National Weather Service composite hourly radar summary charts transmitted by facsimile circuit were collected for a period from July 15 through August 6, 1971. The charts are prepared from two sources. East of the Continental Divide, the information comes from the weather radar network, whereas to the west, radar echo information is obtained from radars operated by the FAA Air Route Traffic Control (ARTC) network [39]. Distribution of the latter stations along with their respective areas of coverage are shown in figure A1. Total areal coverage is apparent throughout the southwest with the two small indicated exceptions. Statements by regional observers claim that the accuracy of echo location within the indicated 100-mile radii is less than 5 miles.

For the period of data used in this study, the series of radar summary charts were incomplete because of facsimile schedules and malfunctions. The 122 charts considered in this study for Arizona and New Mexico are listed in table A1.

Correlation of echoes with terrain classification

As a means of analysis, the States of Nevada, Utah, Arizona, and the portion of New Mexico (west of longitude 107° 20') were subdivided by a grid whose units were one-third of a degree per side. At these latitudes this grid resulted in squares approximately 15-20 miles on a side. This grid was applied to the radar summary charts and a 1:7,000,000 topographic chart with contour interval of 1000 ft. Each grid square of the topographic map was analyzed somewhat subjectively for mean elevation, and for the degree of terrain roughness. The latter was determined according to the guidelines given in table A2. The distribution of squares according to the terrain roughness classification for the four states is shown in figure A2. A few of the noteworthy terrain features appearing on these analyses are the diagonal axis of rough squares across Arizona consistent with the Mogollon ridges, the large smooth area in eastern New Mexico that is part of the Great Plains, and the marked dominance of roughness in Nevada and Utah.[1]

The total number of radar echoes occurring over rough, intermediate and smooth squares were tabulated separately for each state. A comparison was made between the observed frequencies and the number that would be expected from a random distribution. These comparisons are presented in table A3 along with evaluations of the level of significance determined from testing the null hypothesis that radar echoes occur independent of terrain roughness. Chi-square values greater than 9.21 are significant at the 99-percent level to reject the null hypothesis of independence. Based on these criteria, only Utah appears not to support a relationship between echo frequency and terrain classification. The most dependence of echo frequency to terrain is shown by a combination of data from the four-state area.

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[1] A survey flight initiated by the San Francisco District of the Corps of Engineers, was made over portions of the Southwest States, in May 1972, after this pilot study was completed. The primary purpose for the flight was to give two accompanying members of the Hydrometeorological Branch a more realistic impression of terrain features than is obtainable from maps. Conclusions reached after this flight suggest that the scale of map used for analysis is not completely realistic. However, inadequacies in radar echo data compensate to some extent, such that great detail may not be warranted.

This simple evaluation is reasonable support for a relationship between echo occurrence and terrain roughness. The exception of Utah to this conclusion is not immediately understood; however, possible reasons may lie in the limited data sample, or with effects of "drifting." The latter mechanism implies that an echo formed over rough terrain under suitable wind conditions was transported over smoother terrain. It is acknowledged that drifting is likely in all locations, but particularly in Utah do the synoptic circulation patterns support drifting.

Echo count vs. elevation

In the second phase of this study, consideration was given to the variation of echo count with elevation. First, the count of the number of echoes for the period analyzed over each grid square was determined. Then the elevations of the grid squares contributing to each echo count were averaged. The results of this analysis have been plotted in figures A3 to A6 for western New Mexico, Arizona, Nevada, and Utah, respectively. For clarity it might help to give an example of what the figures represent. Referring to figure A3, an echo count of 15 is plotted against an elevation of about 6900 ft. This elevation is the average elevation of 5 grid squares, each of which had a total count of 15 echoes during the period. Although the scatter of points is quite large, particularly at the higher echo counts, the data can be represented by mean curves as indicated (approximated by "eye"). In each of the four states, these curves show a direct relationship between increasing echo occurrence and increasing average terrain elevation. One of the obvious differences that appear in these results is the indication that in Arizona and western New Mexico the count increases with average elevation beyond 8000 ft, while in Utah and Nevada no difference in echo count is implied above elevations of about 6500 feet. The difference in the plots are not readily explainable. Arizona and New Mexico being closer to the moisture source, and the other two states farther removed, may account for fewer clouds at high elevation over Utah and Nevada. In moist air nearer the tropics clouds can build up higher. It is thus possible that drifting of higher clouds in New Mexico and Arizona account for a greater count at high elevations in these states.

The dispersion in Utah in elevations for squares with echo counts greater than 13 warrants investigating each individual square. It is possible that some well exposed to southerly moisture have a high count, others may have a low count because of sheltering by nearby mountains.

Artificial division by state boundaries may have a bearing on the relations found.

In any case, we are investigating reported cloud echoes which have some but not direct bearing on rainfall. Even if additional data confirms the relationship and a direct relation between echo frequency and rain frequency is assumed, rains would be of the everyday category. The results only confirm the well-known fact that rains are more frequent on slopes. In general, slopes increase with elevation.

Possible explanation of differences in the echo count - elevation relationship led to attempts at identifying echo drifting during the period studied. Individual radar summary charts were reviewed towards noting hour-by-hour variations in echo position. Analyses from overlay tracings of selected series proved the difficulty in tracking individual echoes. It was, in general, impossible to identify specific echoes from one map to the next because of the multitude of individual echoes comprising the hourly summaries, Nevertheless, in some instances where relatively small clusters of echoes appeared isolated from the overall confusion, it was possible to show movement of the echo cluster. However, it was impossible to determine whether drifting was more frequent in any one region over that in any other region. In those instances when drifting was evident, comparison with upper winds disclosed that the echo movement was best represented by the 500-mb wind pattern. In this regard, it is to be remembered that during the summer months the 500-mb pattern shows a warm-core anticyclone centered generally above the surface thermal low. This position results in northwest to northeast 500-mb winds over New Mexico, southwest to west winds in Nevada, west to north-west winds in southern Arizona with negligible motion near the Utah-Arizona juncture.

Subsequent to this investigation a copy was received of an unpublished report by J. E. Hales [40] on a similar, though more complete, analysis of radar echo summaries. Mr. Hales, at the Phoenix Weather Service Office, took July and August radar summary charts (24 per day) for 1970 and 1971, and determined the frequency of occurrence of echoes on a grid unit covering Arizona. His conclusions, in part, support the tentative results of the present study in that the greatest frequencies of occurrence of echoes are observed over the mountains. However, as a result of having a more consistent data sample, Hales was able to show that the area of maximum echo frequency exhibits a diurnal shift from mountain peaks in early afternoon to desert areas in late evening. The conclusion is that the early advantage to insolational heating contributes to the daytime maximum over the mountains. However, as the deserts receive late afternoon heating, convective activity increases over these areas toward evening. Private communication with Mr. Hales confirmed that this diurnal shift was not a gradual drift off the mountain slopes, but in most cases it was caused by two pseudo-independent developmental conditions.

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TABLE A1

RADAR ECHO CHARTS ANALYZED FOR ARIZONA AND NEW MEXICO

		Hour of the day (MST)#																							
JULY		00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
15	A.					*		*	o			o			*			*						*	
	N.M.					o		o	o			o			*			*						*	
16	A.		*	*	X	o		o	o			X			*										
	N.M.		*	X	o	o		o	o			o			*										
17	A.																								
	N.M.																								
18	A.																	*						*	
	N.M.																	*						*	
19	A.		*			o						o			*										
	N.M.		*			X						o			*										
20	A.		*			X		X													*		NA		
	N.M.		*			X		X													*		NA		
21	A.		o	o	o	o		o	o																
	N.M.		*	X	X	X		X	o																
22	A.					*		*							*			*						*	
	N.M.					*		*							*			*						*	
23	A.		o	o	o	o		o							*										
	N.M.		*	*	o	o		o							*										
24	A.																								
	N.M.																								
25	A.																							o	
	N.M.																							*	
26	A.		o	o	o	o		o	o			o			*			*							
	N.M.		*	*	*	*		*	o			*			*			*							
27	A.		X	o	o	o		o	o			o			*	*		*			*		*	*	
	N.M.		*	X	X	X		X	X			o			*	*		*			*		*	*	
28	A.		o	o	o	o		o	o			X			*	*	*	*					*	*	
	N.M.		o	*	o	o		o	X			*			*	*	*	*					*	*	
29	A.		*	*	o	o		o	o						*	*		*					*	*	
	N.M.		*	o	o	o		o	o						*	*		*					*	*	
30	A.		*	o		o		o	o			o			*	*	*								
	N.M.		*	*		*		*	o			o			*	*	*								
31	A.																								
	N.M.																								
AUG 1	A.																							*	
	N.M.																							*	
2	A.		*	*														NA							
	N.M.		o	o														NA							
3	A.			*	*	*		*	*			o			*								*	*	
	N.M.			o	o	o		*	o			*			*								*	*	
4	A.		*	*	*	*																		*	
	N.M.		o	o	o	o																		*	
5	A.					*																		*	
	N.M.					X																		o	
6	A.					*			*			o													
	N.M.					X			X			*													
Totals			12	11	9	16		11	11			9			11	4	2	8			2		5	11	=122 charts
Nu. of echoes			11	11	6	12		7	4			5			11	4	2	7+			2		4+	11	
% echoes			92	100	67	75		63	36			55			100	100	100	100			100		100	100	

Legend:

\# actual time of radar summary chart is 45 min. after each hour; e.g., 10 = 1045 MST

* echo classed thundershowers

X echo classed rain showers

o no echo

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TABLE A2

TERRAIN ROUGHNESS CLASSIFICATION

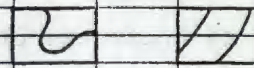
TERRAIN CATEGORY	DESCRIPTION OF TERRAIN	ILLUSTRATIONS OF TYPICAL TERRAIN
ROUGH	Two complex or, three or more smooth contours	
INTERMEDIATE	One complex or, two smooth contours	
SMOOTH	No contours or, one generally smooth contour	

TABLE A3

SIGNIFICANCE TEST OF DISTRIBUTION OF RADAR ECHOES RELATIVE TO TERRAIN CLASSIFICATION

TERRAIN CATEGORY	ARIZONA obs.[1]	ARIZONA exp.[2]	W. NEW MEX. obs.	W. NEW MEX. exp.	NEVADA obs.	NEVADA exp.	UTAH obs.	UTAH exp.	COMBINED SW obs.	COMBINED SW exp.
ROUGH	994	943	323	279	1839	1783	1256	1245	4412	4233
	135*		32		224		160		551	
INTERMEDIATE	810	831	368	392	319	350	197	210	1694	1805
	119		45		44		27		235	
SMOOTH	40	70	32	52	102	127	158	156	332	400
	10		6		16		20		52	
TOTALS	1844	1844	723	723	2260	2260	1611	1611	6438	6438
	264		83		284		207		838	
χ^2	17.69		19.38		10.83		1.03		28.08	

LEGEND

1 no. of observed echoes

2 expected if echoes occurred randomly; e.g., $\left(1844 \times \frac{135}{264}\right) = 943$

* no. of unit squares in category

χ^2 — reject the null hypothesis that echoes occur independent of the terrain classification if value is greater than or equal to 9.21 for 1% level of significance and 2 degrees of freedom.

APPENDIX B

ANTECEDENT RAINFALL

The subject of antecedent rainfall amounts, in this case, rainfall that precedes an extreme rain event, is of specific interest to the Corps of Engineers office in the Southwest. This interest primarily arises from concern that rains falling a certain number of hours prior to a major event may contribute significantly to the soil saturation and thus increase the subsequent runoff.

By antecedent rainfall, this study is primarily one dealing with the timewise sequence of rain events at a particular location. At present, there is no basis for determining how much or at what time interval prior to a major event antecedent rainfall can occur. Common experience suggests that in shower-type conditions bursts of rain are observed without regard for length of the intervening interval. The question arises, naturally, whether, and to what extent, antecedent bursts occur as the total rainfall in any one burst approaches the PMP.

One possibility is to evaluate the vast quantities of hourly data for frequency information on joint occurrences of shower-type rains and the time intervals separating these events. But, it is not easily understood how the results of such an analysis could be extrapolated to the PMP-type event. Rather, the approach used in studies of antecedent rainfalls for drainage basins in the Eastern States has resulted from consideration of more extreme precipitation events. For the eastern basins, such studies have benefited from greater density of hourly recording stations and the larger number of extreme events.

Of the extreme thunderstorm events listed in table 1, the Campo storm gives the best example of antecedent rainfall. Midday showers were recorded by the observer on each of 8 consecutive days, of which the extreme event of 11.5 inches occurred on the third day. The record shows that a shower of 0.20 inch occurred between 1300 and 1400 on the 11th, roughly 21.5 hours prior to the extreme thunderstorm. On the 10th, 0.30 inch fell between 1200 and 1300. An even larger amount, 1.05 inches, was noted to occur 23.5 hours after the extreme event on the 13th. Table B1 shows the Campo observer's reports for the 8-day period that constituted the total rainfall for the month.

Table B1.--Daily Rainfalls at Campo, California

Date	Time of precipitation (PST)	Amount (inches)
Aug. 10, 1891	1200-1300	0.30
11	1300-1400	0.20
12	1140-1300	11.50
13	1230-1330	1.05
14	1140-1300	0.50
15	1210-1305	0.75
16	1315-1430	1.05
17	1205-1400	0.75

For the purposes of antecedent rainfall consideration, the entire record of table B1 could be inverted to show rainfall on each of 5 preceding days, thereby increasing soil moisture prior to the major event.

Concerning synoptic weather conditions during this 8-day period, little change was evident from the sparse data available. It appears feasible from the synoptic aspect that the larger shower reported the day after the extreme storm could have occurred with equal likelihood on the preceding day, the 11th.

Another large rainfall storm in which significant antecedent rainfall occurred was that at Queen Creek, Arizona [31], mentioned on page 50 . The documentation of this event was better than that of the Campo storm in that rains were observed at seven locations within the vicinity, six of which indicated the time intervals between bursts. These are listed in table B2.

Table B2.--Rainfall in Vicinity of Queen Creek, Arizona

Location	August 19, 1954		August 20, 1954		Interval (hr) between storms
	Rainfall (in.)	Duration (hr)	Rainfall (in.)	Duration (hr)	
C. Weeks Ranch (4 mi. E. of Apache Jct.)	4.5	6	1.5	4	16.5
King's Ranch (7 mi. SE. of Apache Jct. near Superstition Mtn.)	4.93	7	0.17	4	13
Barkley Ranch #1 (10 mi. E. of Apache Jct.)	3.5	6.5	2.6	2	19

Table B2.--Continued

Location	August 19, 1954 Rainfall (in.)	August 19, 1954 Duration (hr)	August 20, 1954 Rainfall (in.)	August 20, 1954 Duration (hr)	Interval (hr) between storms
Barkley Ranch #2 (12 mi. E. of Apache Jct.)	4.5	6	0.4	2	20
Pinal Ranch (6 mi. E. of Superior)	1.64	4.5	1.00	2	16.5
Ray	4.05	2	0.42	?	14
Boyce Thompson Arboretum	5.30	6.5	0.07	?	?

As in the Campo storm, where the extreme rain amount fell prior to a lesser amount, the major Queen Creek storm preceded a secondary rain such that, because of the apparent lack of synoptic weather change, the order of fall could have been reversed for the purpose of an antecedent rainfall study. For the latter storm, the largest antecedent rainfall is 33 percent of the major burst amount (4.5 in.) for those observations exceeding 4 inches.

Other data sources

Leopold [41] in a paper on heavy rains in Arizona and New Mexico provided a tabulation of 72 intense summer storms (rainfalls > 2 inches). From the list of 72 cases, only 24 exceeded 3 inches and occurred in July and August. Of the latter, only 10 occurred west of the Continental Divide, and of these 10, only three were found to have antecedent rainfalls (no records for two stations). The three cases of antecedent rainfall were:

Location	Date	Major event		Antecedent event*	
		Amt.	Dur.	Amt.	Dur.
Sierra Ancha, Ariz.	Aug. 5, 1939	2.66	2.5	0.15	?
Santa Marquerite, Ariz.	Aug. 22, 1935	4.10	1.5	0.1	?
Crown King, Ariz.	Aug. 6, 1918	5.05	11.5	T	?

*Antecedent is 24-hour amount from Climatological Data record for previous day.

The rainfall at Crown King lasting 11.5 hours is suspicious in that the event may reflect a more general-type moisture surge than the typical summer thunderstorm considered in this study.

Finally, an attempt to gain additional cases was made through a survey of "Hourly Precipitation Data" for Arizona and western New Mexico from January 1952 to September 1970. Bursts up to 6 hours were noted for which rainfall of 1 inch or more occurred in at least 1 hour and having antecedent rains within a 24-hour interval. The relatively few cases satisfying these conditions are listed in table B3.

The last column gives the percentage that the antecedent amount is of the major 6-hour amount.

Table B3.--Series of Two-burst Data from Hourly Rainfall

Location	Date	Major Burst Amt. (in)	Major Burst Dur. (hr)	Antecedent burst Amt. (in)	Antecedent burst Dur. (hr)	Interval (hr)	% of Major Burst
ARIZONA							
Petrified For.	7-23-54	2.20	2	0.28	1	6	13
Santa Rita	8-16-66	1.13	5	1.04	4	2	92
Nogales	8-17-66	1.12	4	0.76	5	15	68
Cochise PH	7-23-64	1.09	2	0.40	4	11	37

Table B3—Continued

Location	Date	Major Burst Amt. (in.)	Major Burst Dur. (hr)	Antecedent burst Amt. (in.)	Antecedent burst Dur. (hr)	Interval (hr)	% of Major Burst
ARIZONA							
Bowie Jct.	8-5-63	1.02	2	0.60	2	16	59
Cochise	8-25-63	3.54	4	0.60	?	22	17
Santa Rita	8-22-61	1.50	4	0.43	6	1	29
Payson	8-21-61	2.60	5	0.26	2	23	10
Poland Jct.	8-8-60	1.40	6	0.62	2	23	44
Nogales	9-9-60	1.20	5	0.33	4	15	28
Santa Rita	8-19-55	2.31	2	1.23	4	25	53
Pima	7-16-53	1.06	1	0.64	1	14	60
NEW MEXICO							
Cabezon	9-24-54	2.04	3	0.76	2	16	37
Mogollon	8-3-63	1.33	6	0.54	3	3	41
Mimbres RS	8-12-67	1.34	5	0.65	4	8	49
Hillsboro	8-29-69	0.95	2	0.49	1	9	52
Floyd Lee Rch.	8-2-63	1.34	6	0.23	1	16	17
Mogollon	8-25-63	1.25	5	0.10	5	6	8

In an attempt to derive a relationship for antecedent rainfall, the data from these brief surveys were plotted (major rain vs. time after antecedent) as shown in figure B1. The major burst is plotted on the ordinate, and the antecedent quantity, in terms of percentage of the major burst amount, is plotted according to the time interval reported between bursts. The Leopold data were unsuited to this analysis because information on intervals was not exact. Although the data results in obvious scatter and apparent randomness, it can be seen that, in general, lower percentages are found along the upper major burst amounts and larger percentages along the lower amounts. Since this observation appears to agree with an intuitive conclusion that larger bursts must be separated by longer intervals, envelopes based on the antecedent percentages have been approximated as indicated by the dashed lines in figure B1.

Interpreting the significance of the suggested relationship in figure B1 is the example that if a 6-hour thunderstorm rainfall of 6 inches is considered, a 1.5-inch rainfall could occur 12 or more hours prior to it. By the same reasoning and extrapolating this analysis to include PMP amounts, it is apparent that a 1-inch antecedent rain can occur 16 hours, or a 2-inch antecedent rain can occur 25 hours, prior to a 10-inch PMP. The reliability of these results and their applicability throughout the Southwest cannot be evaluated from the information at hand. The information in figure B1 is offered only as a guide to possible antecedent considerations in the Southwest.

Further antecedent considerations are those regarding storm frequency. Figure B1 deals primarily with shower (burst) frequency. During the warm season in the Southwest and as discussed in section II, the storms commonly are day-to-day thunderstorms and intrusions of tropical moisture surges. The Campo sequence of daily thunderstorms described above is the best example of day-to-day thunderstorms relative to a PMP event and is included in figure B1. The tropical storm surge results in a general-type precipitation condition bringing extensive rains of moderate intensities lasting as long as

24 hours or more. No information exists to indicate how long a period of time is necessary after rains from a tropical surge to establish conditions for a PMP thunderstorm event.

Since the extreme events of record (table 1) all occurred in June to August and the tropical storm surges are generally in September and October, the coincidence of these types of events is lessened. However, as an approximation in the absence of actual data, it is suggested that a time interval comparable to that of mesoscale synoptic conditions is most reasonable. That is to say, a PMP thunderstorm event is improbable less than 3 days after a general-type storm rainfall.

APPENDIX C

CLOUD MERGING

Introduction

The investigation of extreme thunderstorm events in the Southwest, as in other regions, has searched for evidence or factors that might lead to better understanding of the cause(s) and development of these unusual storms. In section II, description of mesoscale features of the few extreme Southwest storms revealed little about the mechanisms that would separate them from the more routine storms.

There is, however, a factor that has been mentioned in many instances of extreme thunderstorm rainfall that may be a clue to their development. This clue comes from the casual accounts of these storms regarding instances of merging thunderstorm clouds. The significance of this observation as a common factor to all extreme rainfall events is unknown. A merging may have occurred but was not observed, possibly observed but not reported, or it may have been obscured by other clouds or darkness.

This appendix reviews some of the reports concerning cloud mergers surrounding extreme events. Few conclusions can be made at this time regarding the significance of these observations. It is hoped that by making note of their relationship to extreme rainfall situations additional interest will be created. As more attention is brought to this phenomenon, further insight as to their rôle in enhancing thunderstorm rainfall should be possible.

Reports

The reports of clouds coming together date back to the beginning of the century and are found in observers' notes as recent as the present. Only recently, with the supplemental observational tool of radar, has the sample of such occurrences appreciably increased. Numerous citings of echo mergings appear in the literature, and they may not, by themselves, be a sufficient condition for causing heavy precipitation.

Typical comments from the literature referring to cloud mergers are the following,

1. Weather Bureau report for Springfield, Oregon, May 25, 1901 [42]

   " . . . at 2 p.m. a black cloud formed in the southeast and moved in a northwesterly direction. Shortly afterward a cloud of like character formed in the southwest and moved in a northeasterly direction. About 4 p.m. the two clouds merged into one and the entire mass moved rapidly in a westerly direction, attended by thunder, lightning, heavy rain, and hail." Hailstones 1.5 in. in diameter along with total precipitation of 1.00 in. were the only additional information noted.

2. Observers notes, Campo, Calif., precip. station August 12, 1891.

See quotation listed on page 9 .

3. Observer account, Palmetto, Nevada, precip. station August 11, 1890, [16].

"On the 11th two intensely black thunder-clouds appeared over the crests of the surrounding mountains. One approaching from the North the other from the East. At a short distance from the camp these clouds seemed to join and rush with extraordinary swiftness towards Palmetto..... A steady column of water poured down, excavating a trench about 500 ft long and varying from zero to seven feet in depth...." Total precipitation reported on this date was 8.8 inches during the 1-hour storm. The "cloudburst" caused complete damage to about 9 miles of stage road, uprooted trees, and dug washes that exceeded four feet in depth.

4. Local observers of Morgan, Utah, storm August 16, 1958.

See quotations listed on page 17 .

5. Published analysis of Walnut Gulch, Arizona, storm September 10, 1967 [43].

"The early cumulus appeared to dissipate, but by 1400 hr two separate groups of heavy cumulus clouds were forming, one system just north and one just east of the upper end of the watershed.... About 1500, the two systems began to move toward each other and by about 1515 intense rain was falling on most of the upper end of the watershed. The two systems combined in the vicinity of Rain Gage 52, and intense rain was recorded there for about 45 minutes." Storm rainfall of 3.35 inches in 45 min was recorded at one point, contributing to record 1500 cfs per square mile peak discharge rates for watersheds in the Southwest.

6. Summary of storms in the Tennessee River watershed with eyewitness accounts of cloud mergings, HMB Report No. 45 [30].

For a study of small-area PMP in the Tennessee River Basin, a list of storms was prepared quoting eyewitness accounts of clouds coming together in 11 extreme rainfall events. [Also mentioned in this report is the eyewitness account of the world-record Smethport, Pennsylvania, storm of July 18, 1942 (30.8+ inches in 4 1/2 hours), in which it is stated it approached the area from several directions.]

7. Published account of thunderstorm echoes, McGill Univ., July 18, 1964 [44].

This paper covers the observations of 12 hours of summer thunderstorms by the McGill University radar. "Patch A" moves onto the map at 1800 and "Patch B" developes on the map at 1845, 75 mm NE of Patch A. At ... (1950),... A + B joins aloft at 20 kft. An hour later ..., Patch B intensifies and rapidly expands aloft and merges with Patch A down to 10 kft, at which time this combined patch contains its maximum total precipitation aloft.... Such a large total precipitation aloft is never attained again." Precipitation was not measured at the surface as part of this study.

8. Published account of seeding cumulus clouds, Miami, Fla., July 16, 1970 [45].

"The natural merger of two cumulus clouds on July 16, 1970, stimulated tremendous growth and rainfall production. The rainfall produced by the

the merged clouds was 22 times greater than that of unmerged pairs. The most striking feature of mergers is the great increase in water production following the union of the clouds. There is a synergistic effect here, an invigoration of the merged system, as a result of which the increase often is far greater than the sum of the water production from the component clouds."

As is evident from the last comments, by Dr. Woodley of the Experimental Meteorology Laboratory in Miami, cloud mergers yield more rainfall than single cells. Although the intensity of rainfall discussed in these storms is much less than the extreme rains noted in the Southwest, it is this conclusion that may be the key to understanding the extreme rainfall event. At present, the dynamic processes that bring about cloud mergers or that cause the multiplication of precipitation after merging are unknown. The fact that they do occur and bring about a result comparable to recorded extremes suggests that more attention should have been given to the comments about cloud mergings made by the earlier observers. Certainly, within the framework of today's forecasting system it is not possible to establish the likelihood of such an event. Radar coverage can monitor precipitation echoes and perhaps will lead to increasing awareness of the frequency and distribution of cloud mergers. It is hoped studies of natural cloud mergers presently being conducted by Dr. Woodley can lead to development of an index of necessary conditions for cloud merging.

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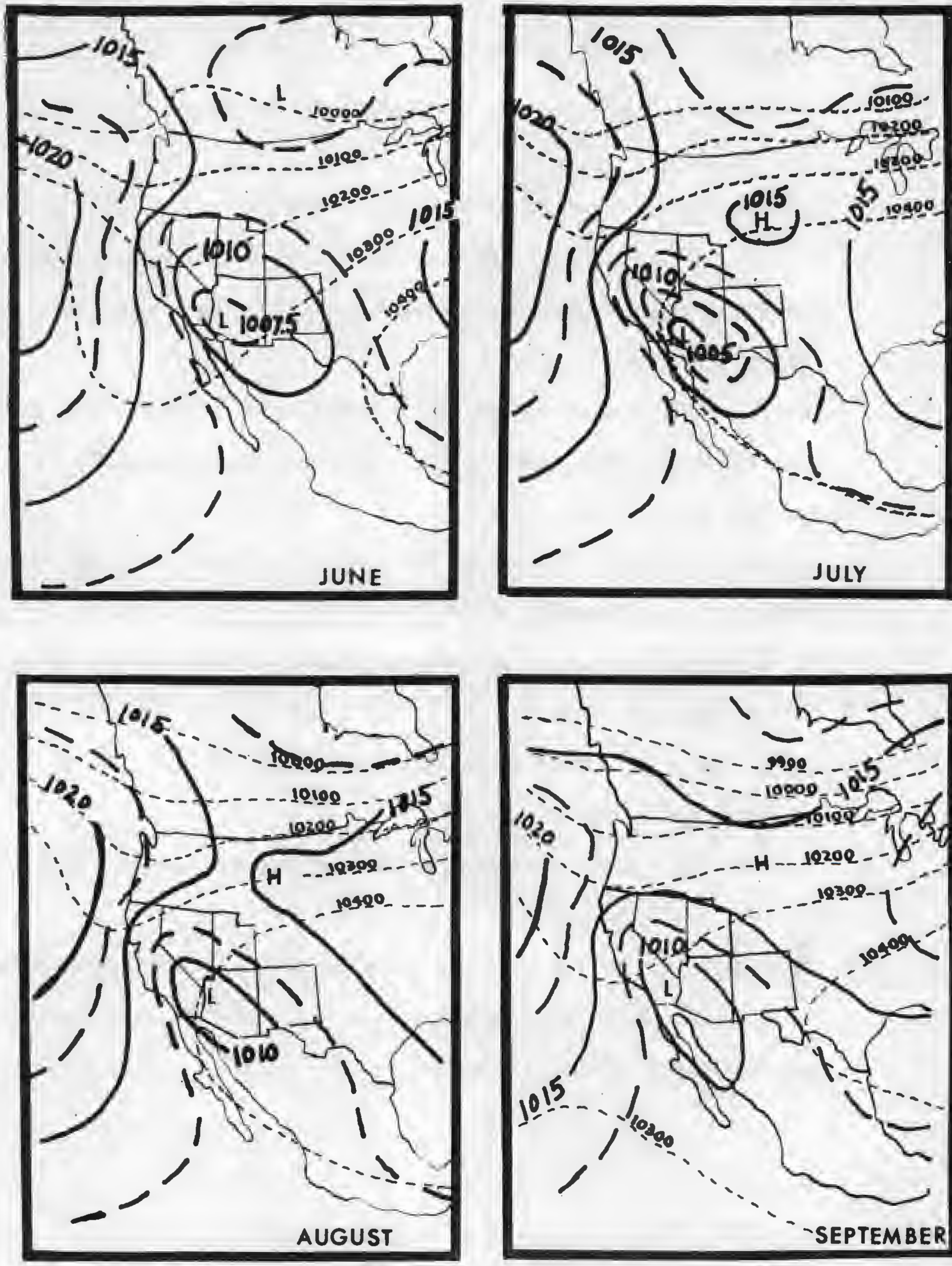


Figure 1.--Normal sea-level pressure patterns. Dashed lines show 700-mb contours in feet.

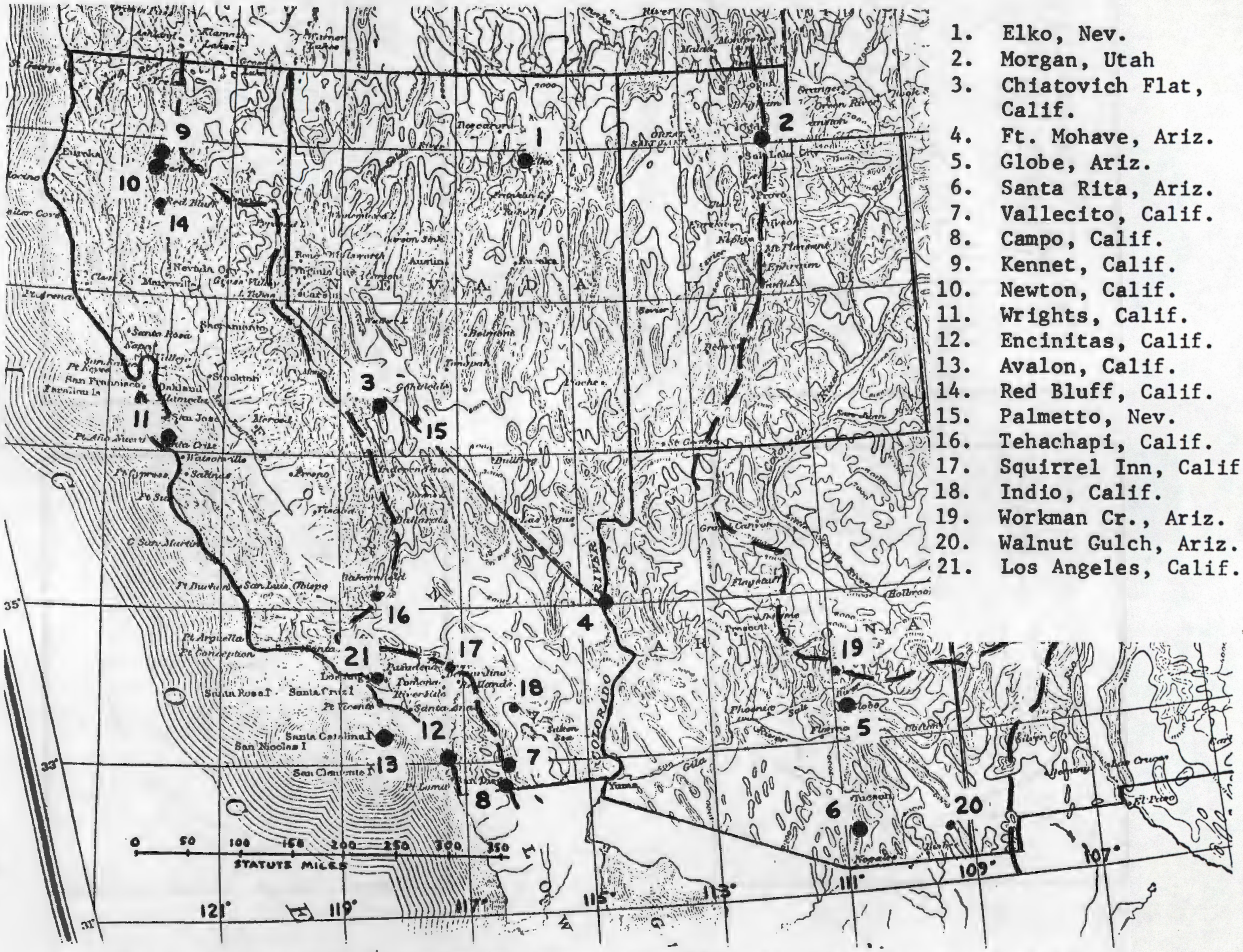
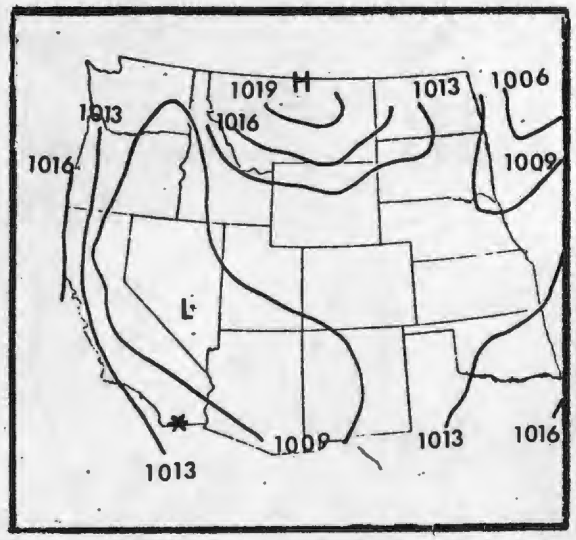
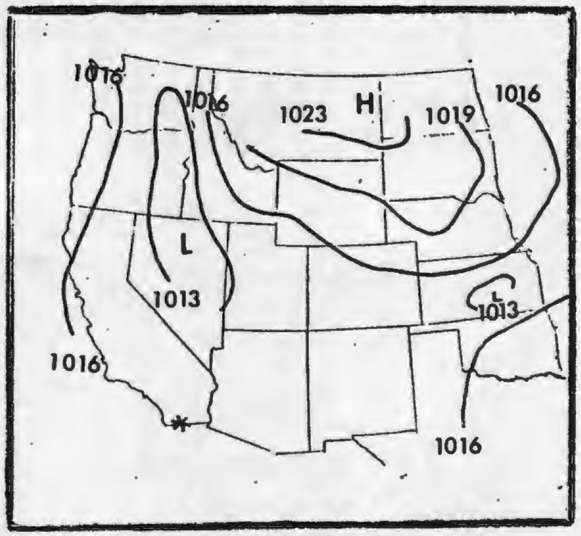


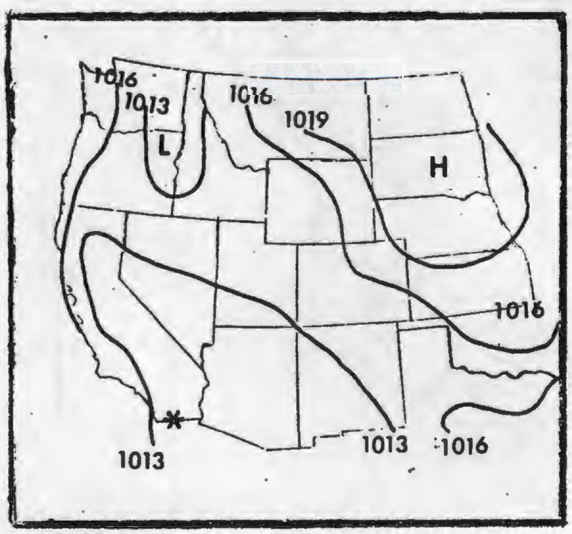
Figure 2.--Locations of extreme short-duration thunderstorm rainfall used in PMP estimates (large dots) and other storms mentioned in text (small dots) including 1000-ft contours and major mountain barriers(dashed lines).



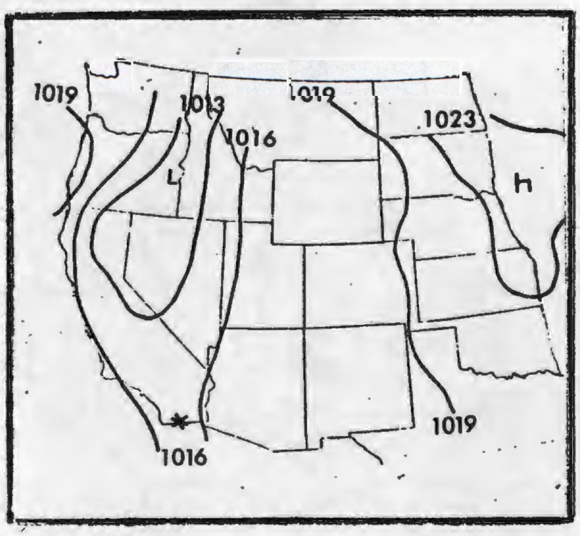
a. Aug. 11, 1891 Sea Level 0100 GMT



b. Aug. 11, 1891 Sea Level 1300 GMT

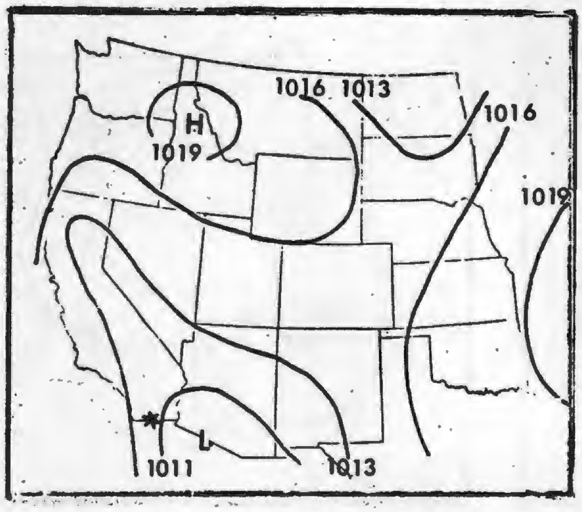


c. Aug. 12, 1891 Sea Level 0100 GMT

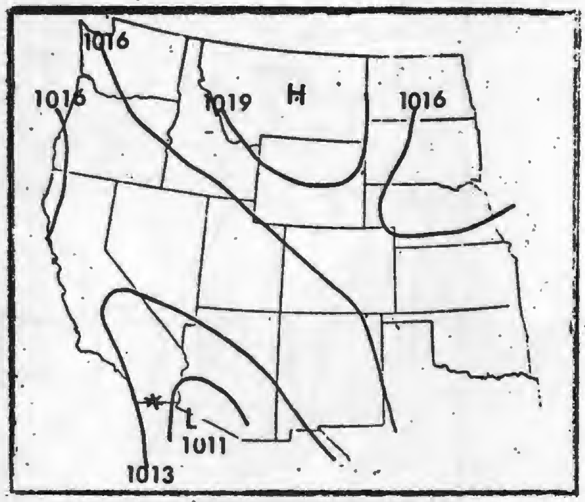


d. Aug. 12, 1891 Sea Level 1300 GMT

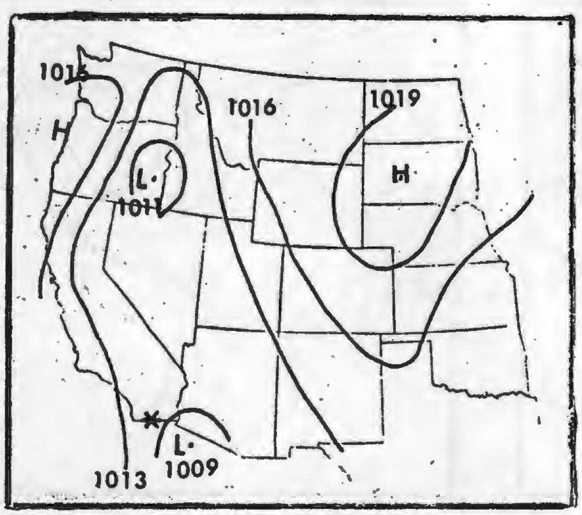
Figure 3.--Weather maps for Campo, California, storm, Aug. 12, 1891



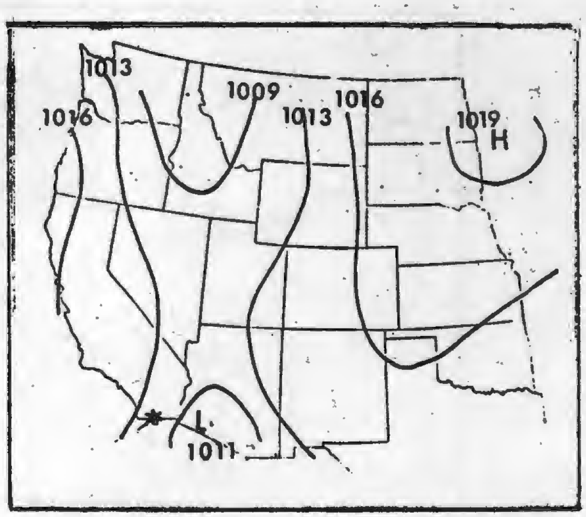
a. Aug. 16, 1922 Sea Level 1300 GMT



b. Aug. 17, 1922 Sea Level 1300 GMT

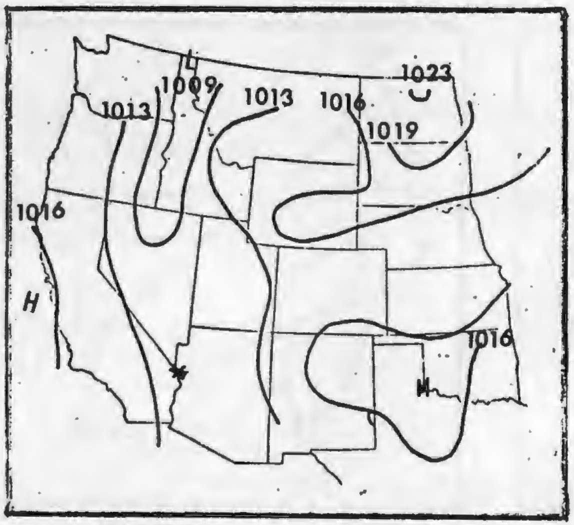


c. Aug. 18, 1922 Sea Level 1300 GMT

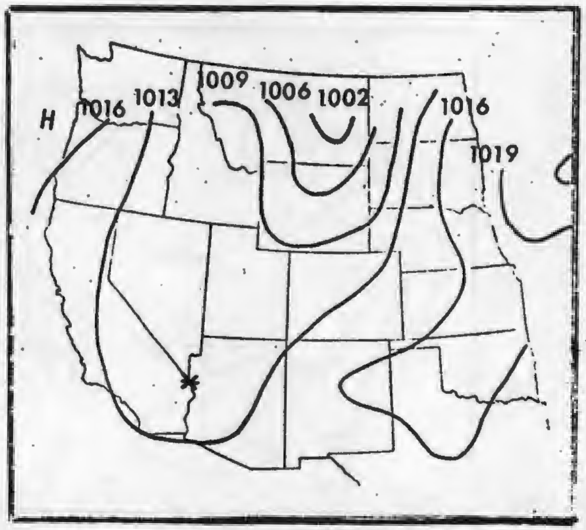


d. Aug. 19, 1922 Sea Level 1300 GMT

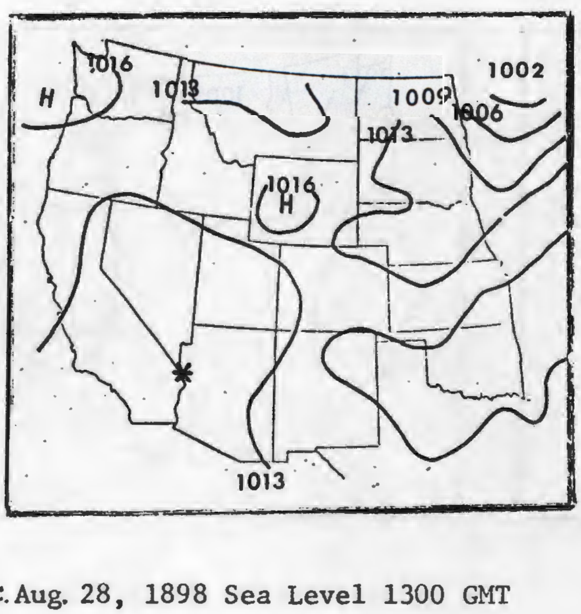
Figure 4.--Weather maps for Campo, California, storm, Aug. 18, 1922



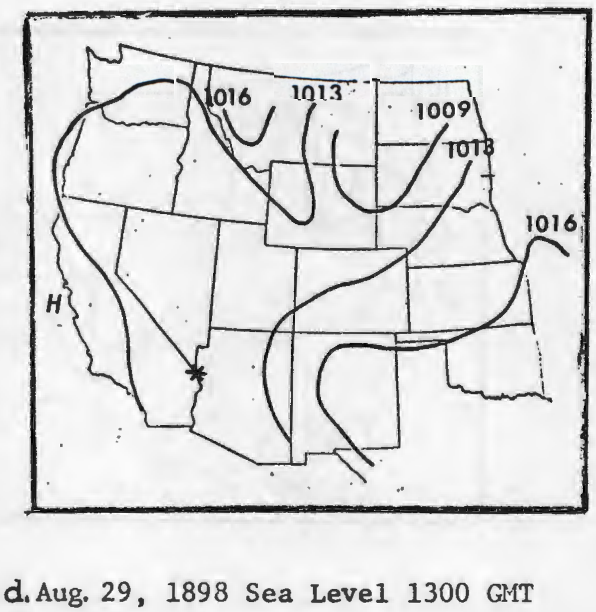
a. Aug. 26, 1898 Sea Level 1300 GMT



b. Aug. 27, 1898 Sea Level 1300 GMT

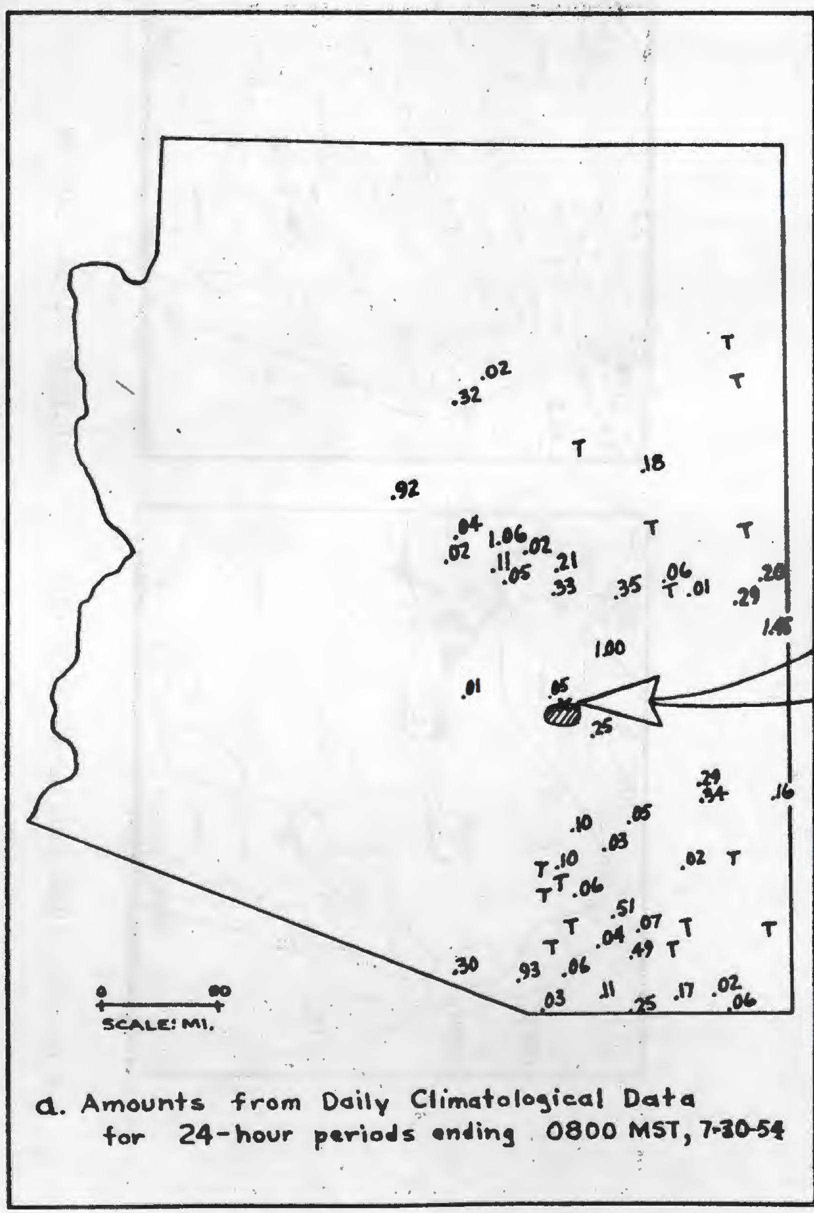


c. Aug. 28, 1898 Sea Level 1300 GMT



d. Aug. 29, 1898 Sea Level 1300 GMT

Figure 5.--Weather maps for Ft. Mohave, Arizona, storm, Aug. 28, 1898



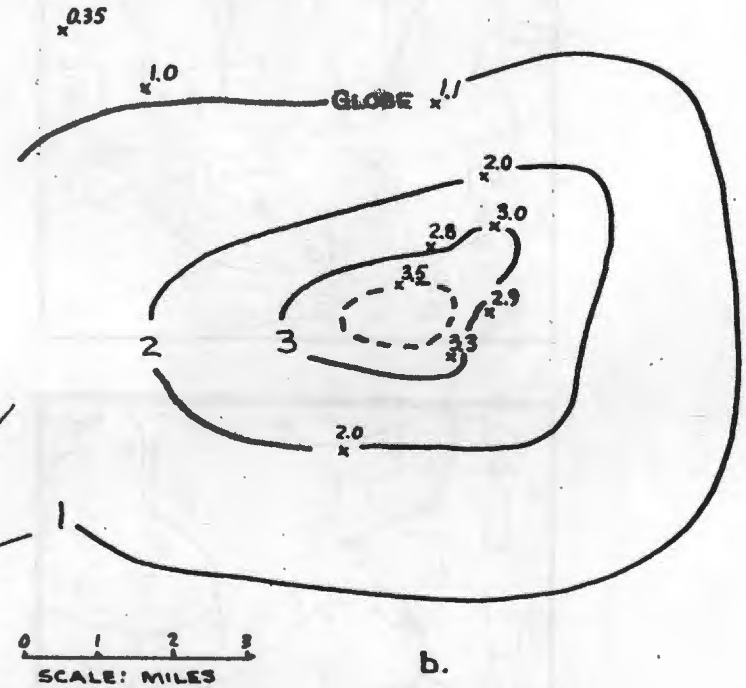
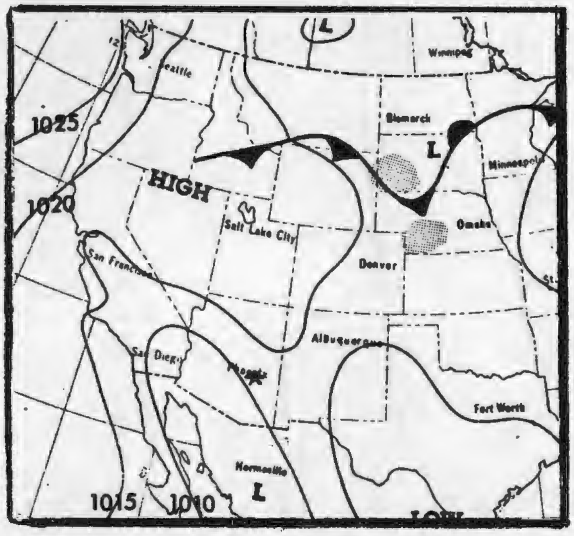
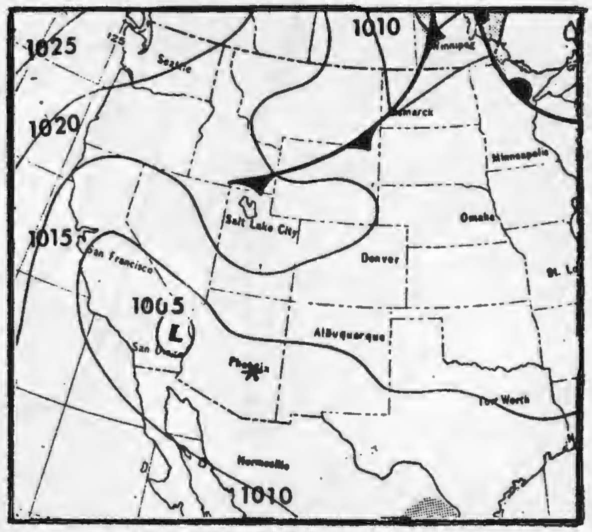


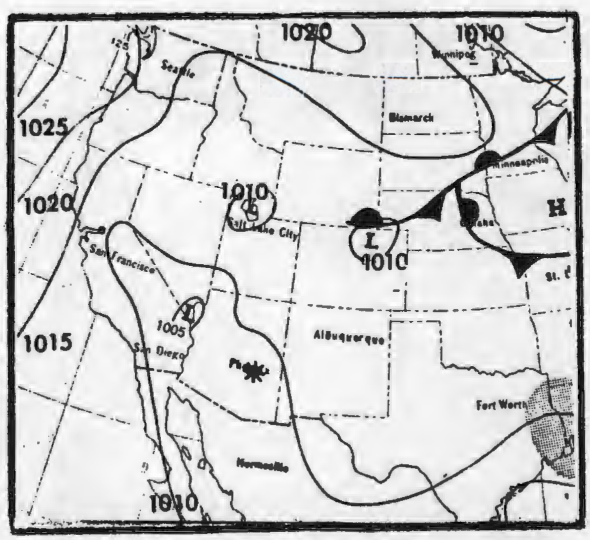
Figure 6.--Precipitation amounts (in.) for Globe, Ariz., storm, July 29, 1954.



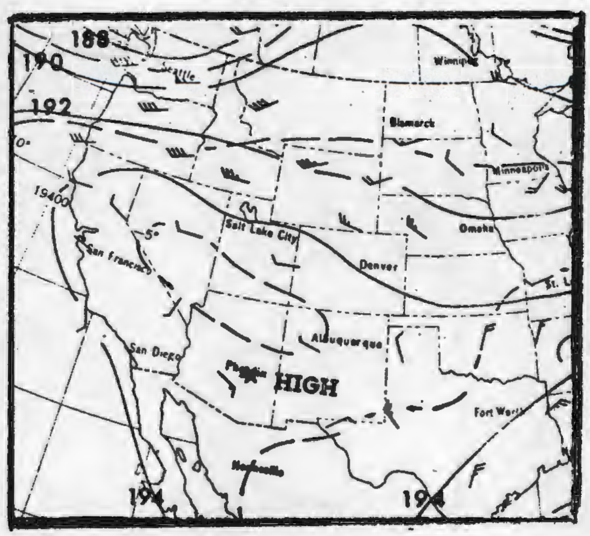
a.Jul. 27, 1954 Sea Level 1830 GMT



b.Jul. 28, 1954 Sea Level 1830 GMT

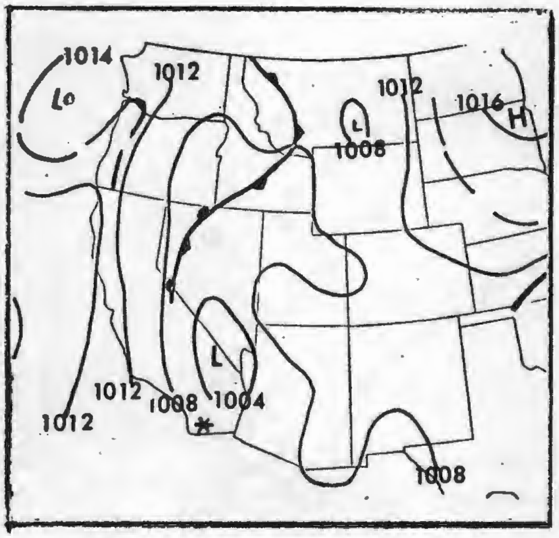


c.Jul. 29, 1954 Sea Level 1830 GMT

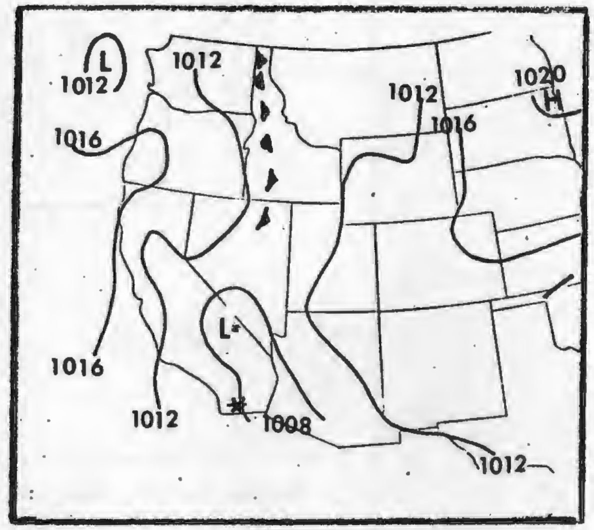


d.Jul. 29, 1954 500 MB 0300 GMT

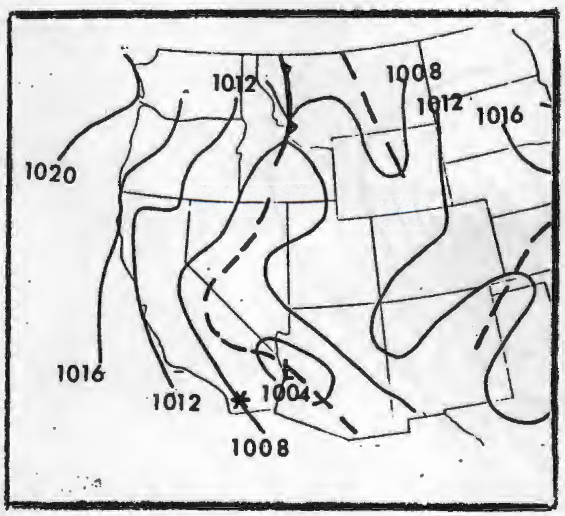
Figure 7.--Weather maps for Globe, Arizona, storm, July 29, 1954



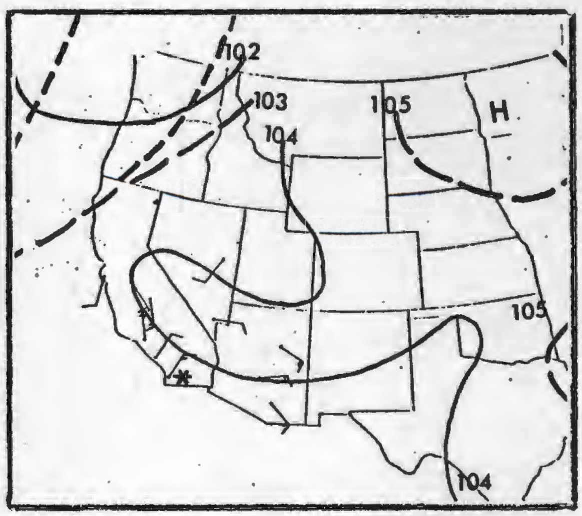
a. Jul. 18, 1955 Sea Level 0030 GMT



b. Jul. 18, 1955 Sea Level 1230 GMT



c. Jul. 19, 1955 Sea Level 0030 GMT



d. Jul. 19, 1955 700 MB 0300 GMT

Figure 8.--Weather maps for Vallecito, California, storm, July 18. 1955

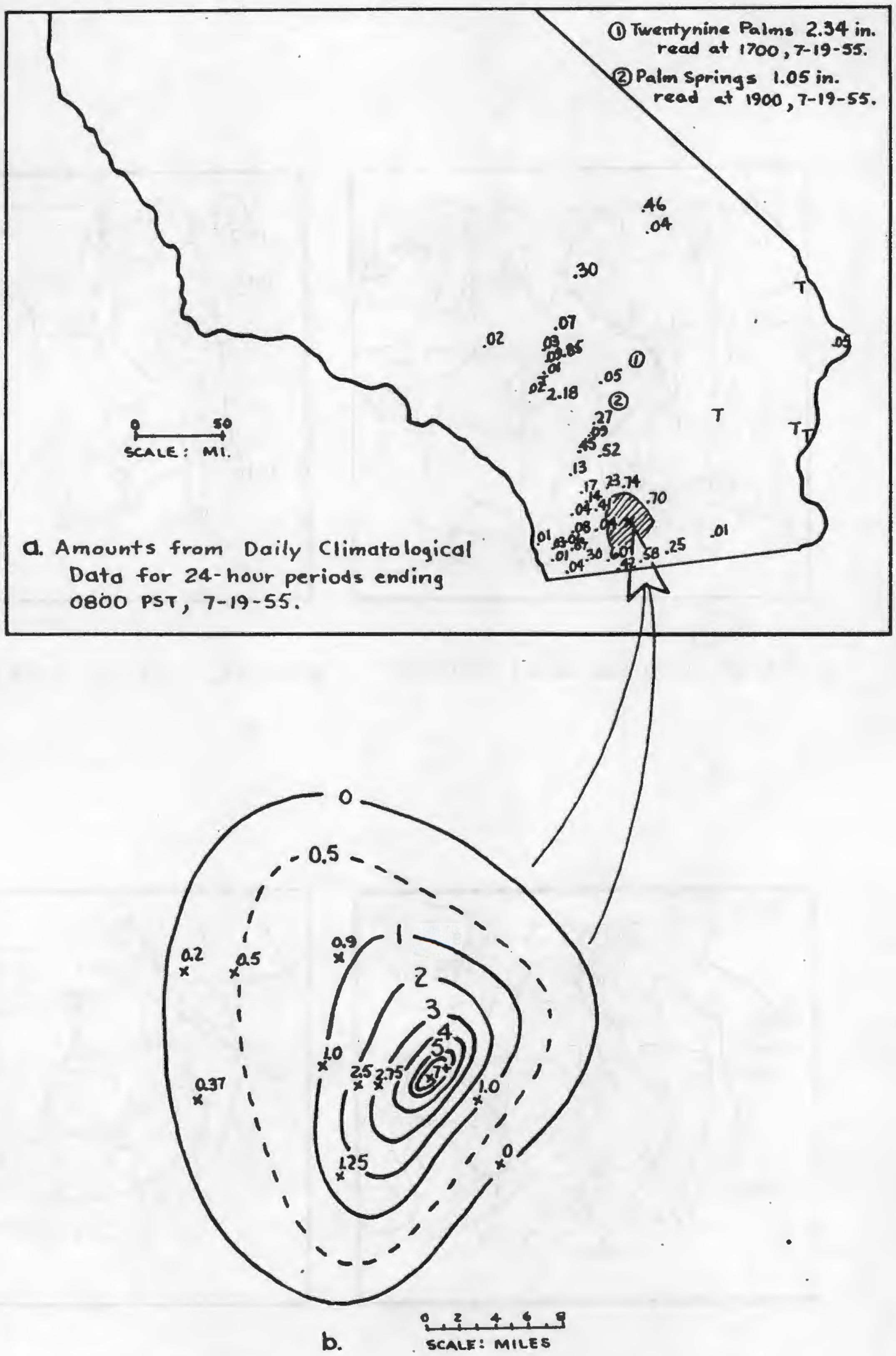


Figure 9.--Precipitation amounts (in.) for Vallecito, Calif., storm, July 18, 1955.

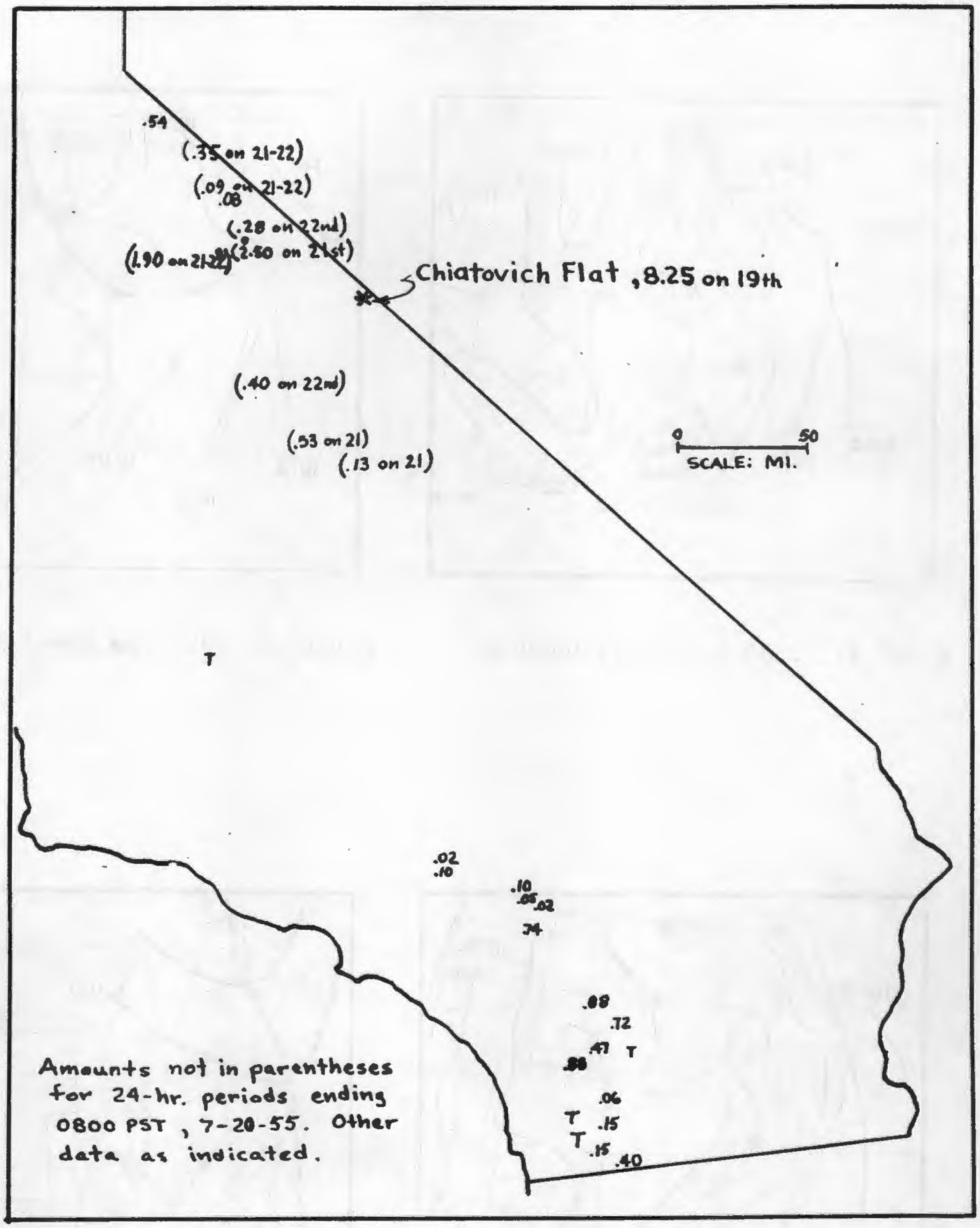
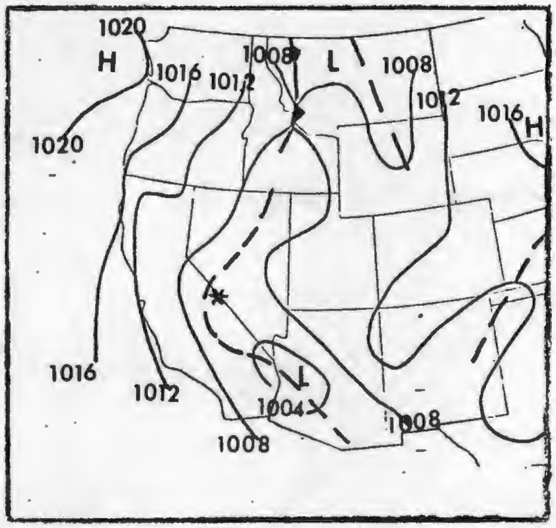
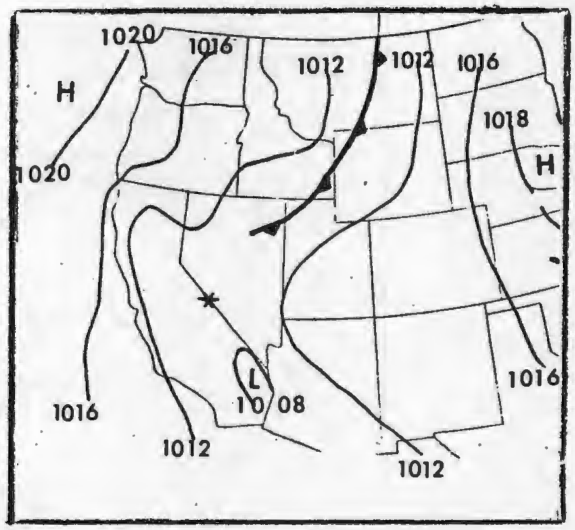


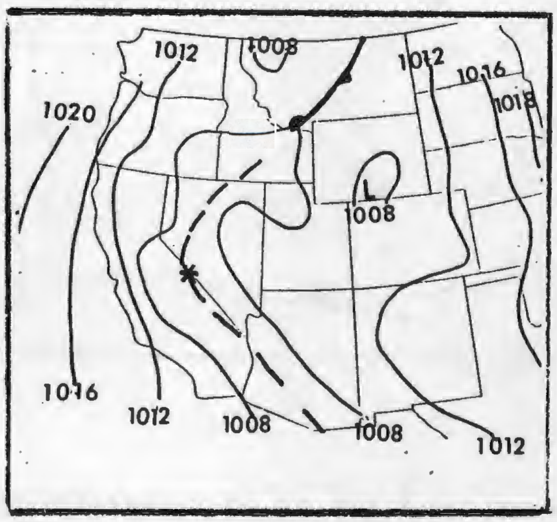
Figure 10.--Precipitation amounts (in.) for day of Chiatovich Flat, Calif., storm, (July 19, 1955) and succeeding days



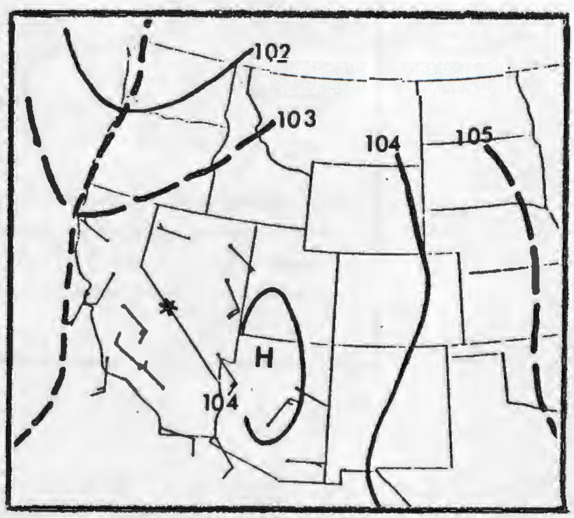
a. Jul. 19, 1955 Sea Level 0030 GMT



b. Jul. 19, 1955 Sea Level 1230 GMT

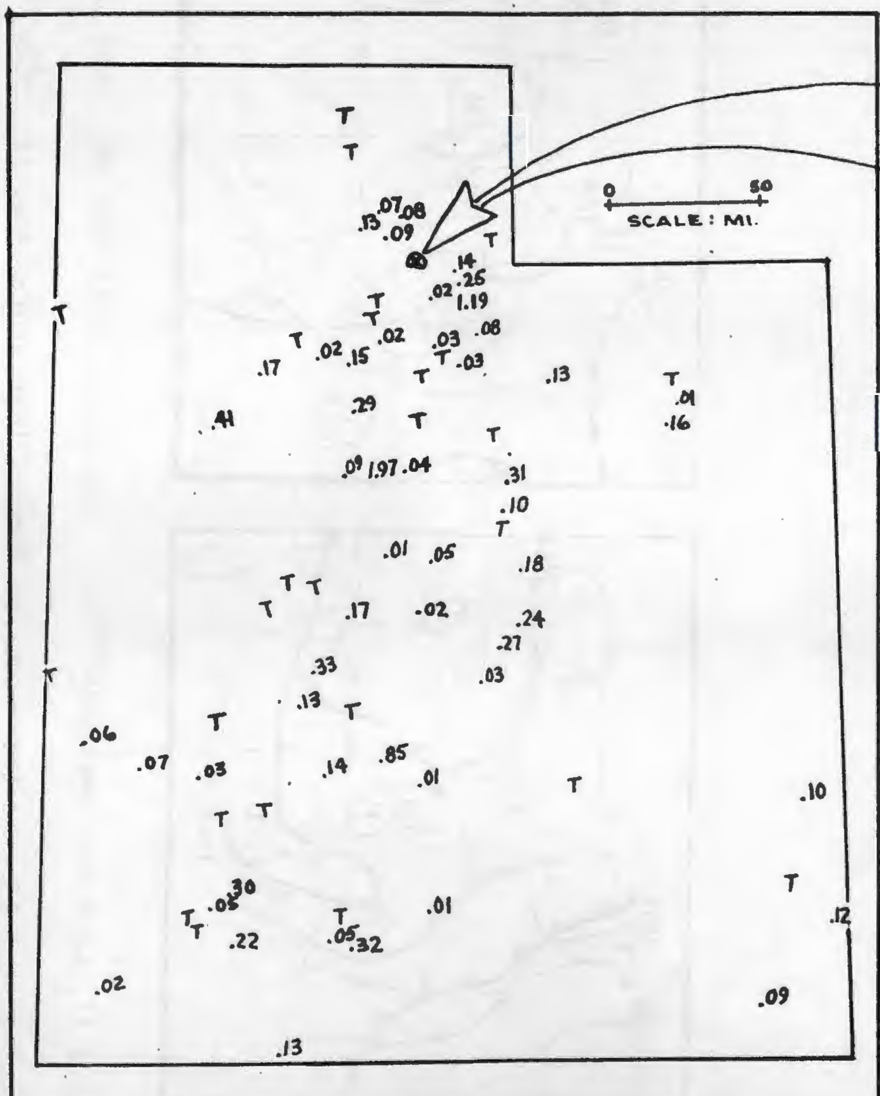


c. Jul. 20, 1955 Sea Level 0030 GMT

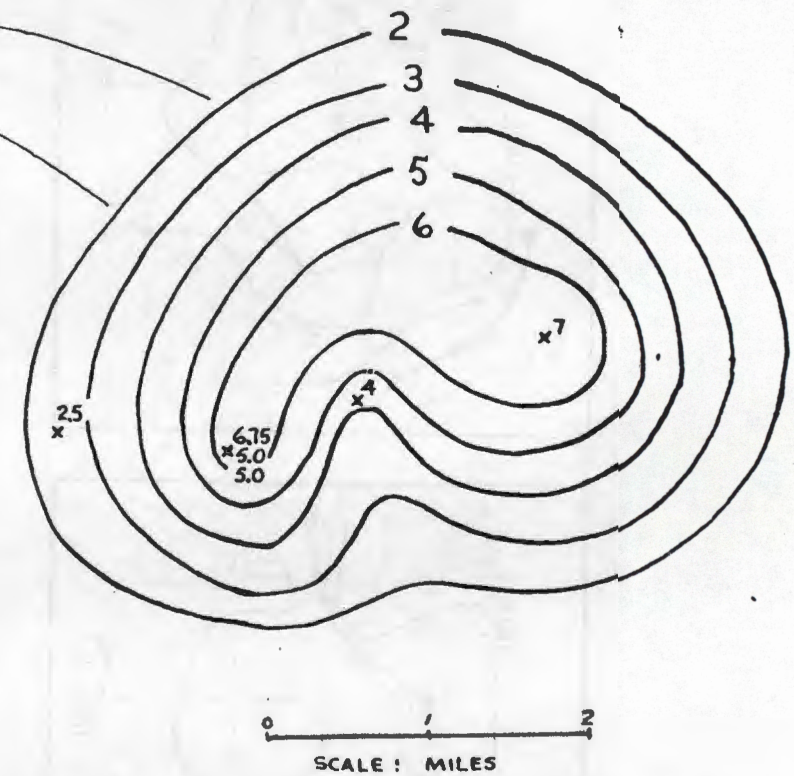


d. Jul. 20, 1955 700 MB 0300 GMT

Figure 11.--Weather maps for Chiatovich Flat, California, storm, July 19, 1955



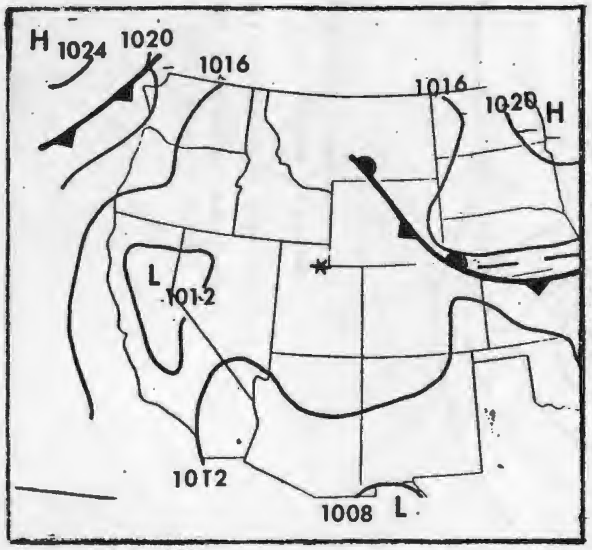
a. Amounts from Daily Climatological Data for 24-hour periods ending 0800 MST, 8-17-58.



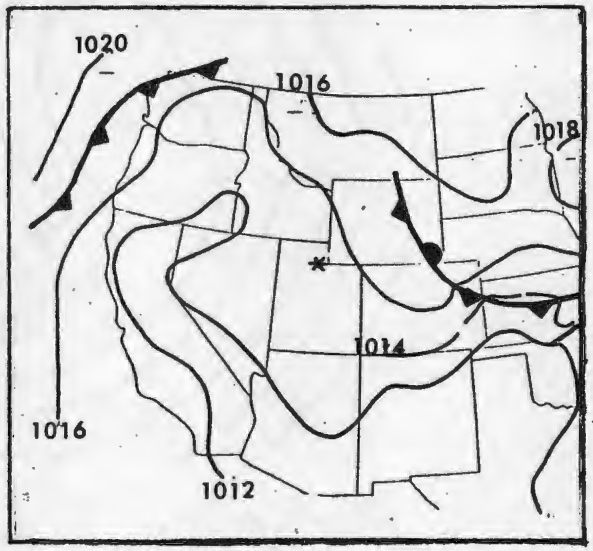
NOTE: Isohyetal pattern includes consideration of runoff intensities by Soil Conservation Service.

b.

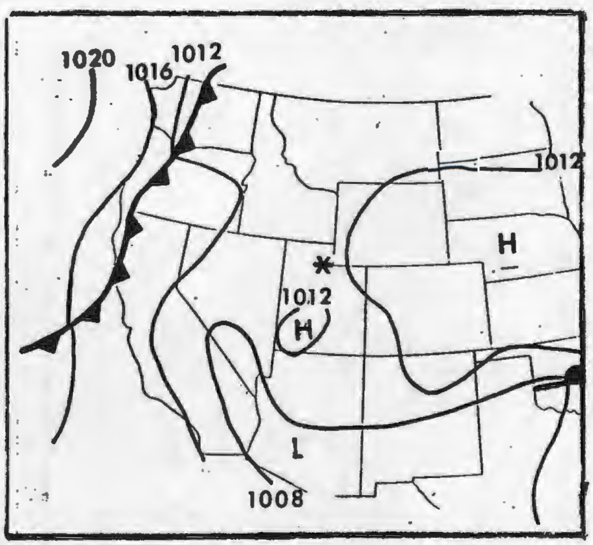
Figure 12.--Precipitation amounts (in.) for Morgan, Utah, storm, Aug. 16, 1958.



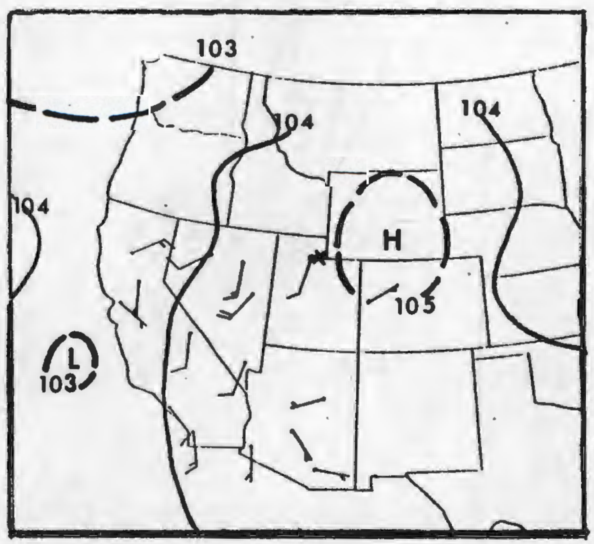
a. Aug. 16, 1958 Sea Level 0000 GMT



b. Aug. 16, 1958 Sea Level 1200 GMT



c. Aug. 17, 1958 Sea Level 0000 GMT



d. Aug. 17, 1958 700 MB 0000 GMT

Figure 13.--Weather maps for Morgan, Utah, storm, Aug. 16, 1958

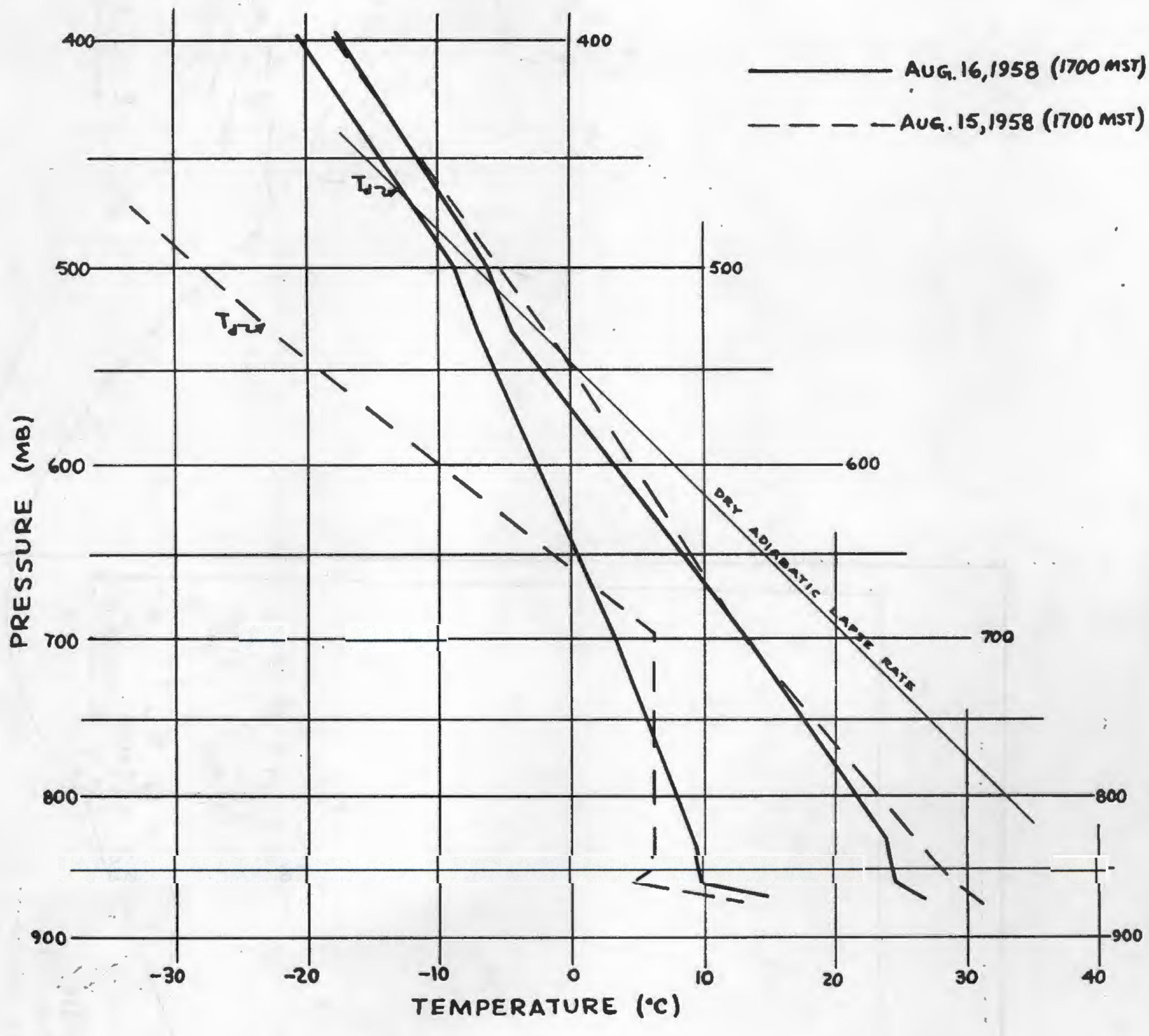


Figure 14.--Temperature/moisture sounding at Salt Lake City.

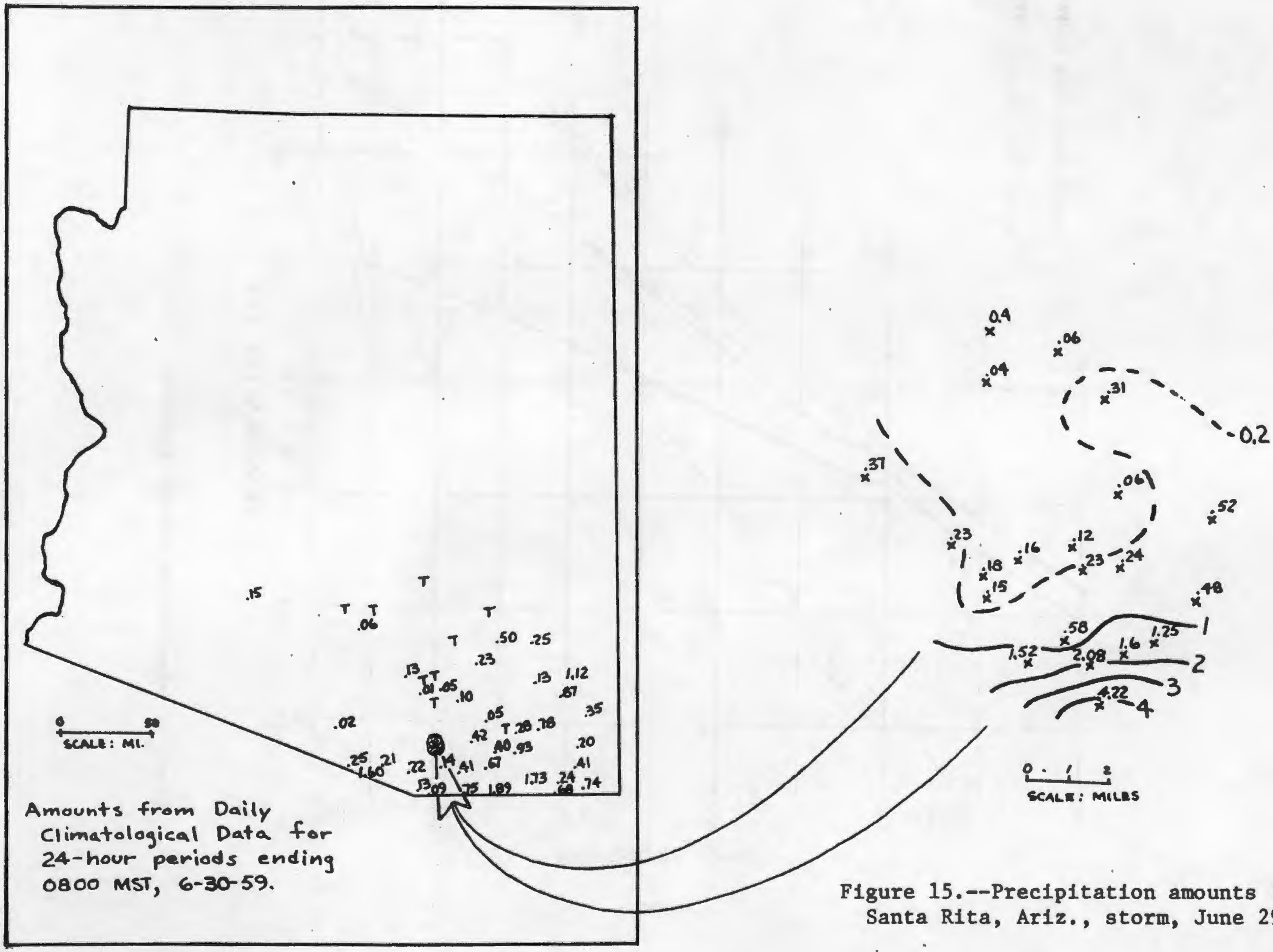
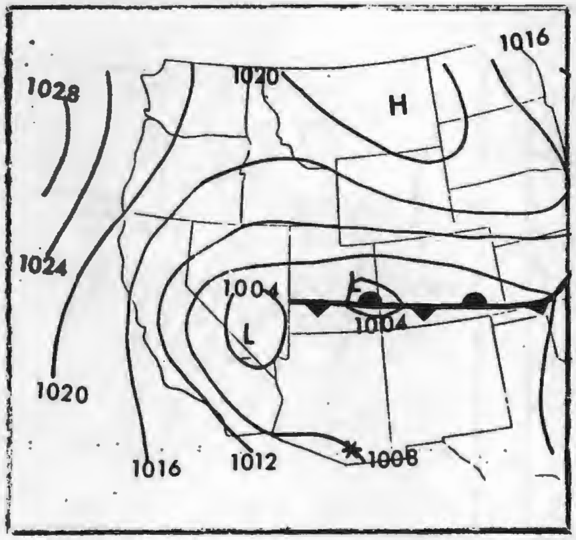
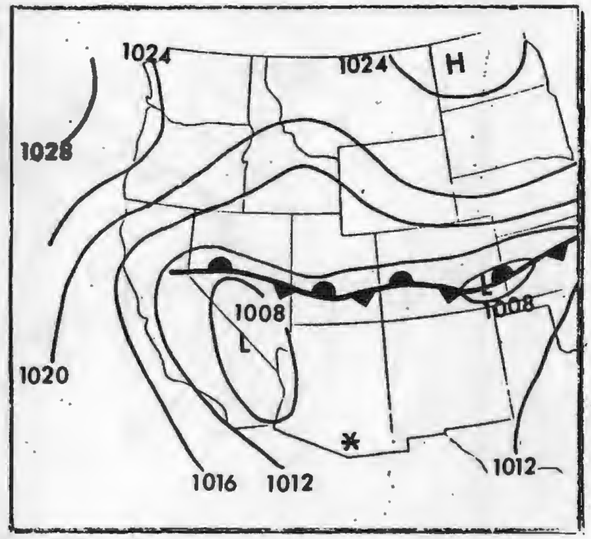


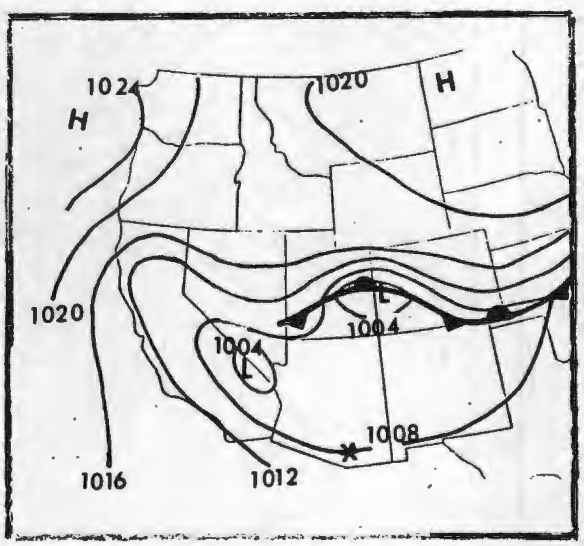
Figure 15.--Precipitation amounts (in.) for Santa Rita, Ariz., storm, June 29, 1959.



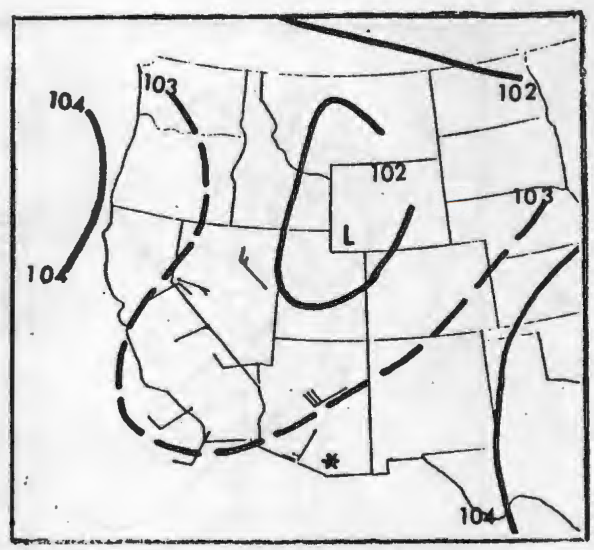
a. Jun. 29, 1959 Sea Level 0000 GMT



b. Jun. 29, 1959 Sea Level 1200 GMT

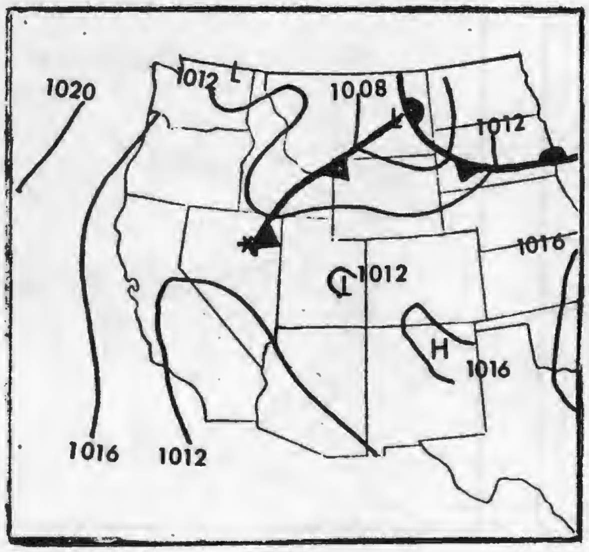


c. Jun. 30, 1959 Sea Level 0000 GMT

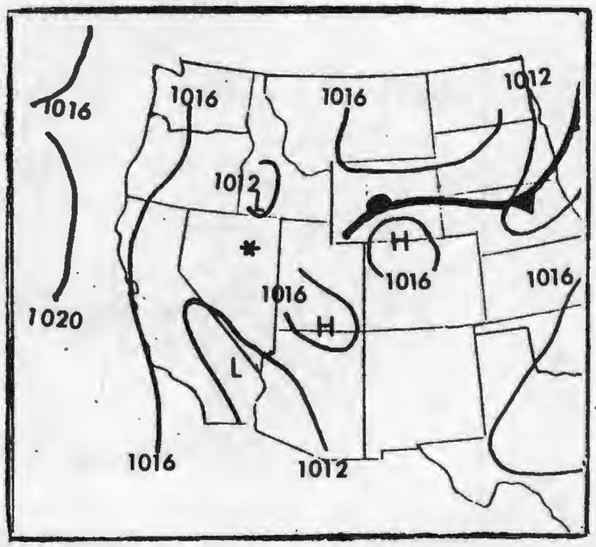


d. Jun. 30, 1959 700 MB 0000 GMT

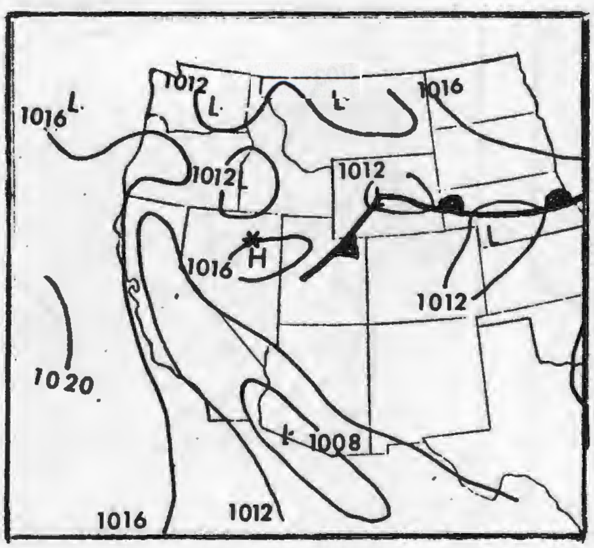
Figure 16.--Weather maps for Santa Rita, Arizona, storm, June 29, 1959



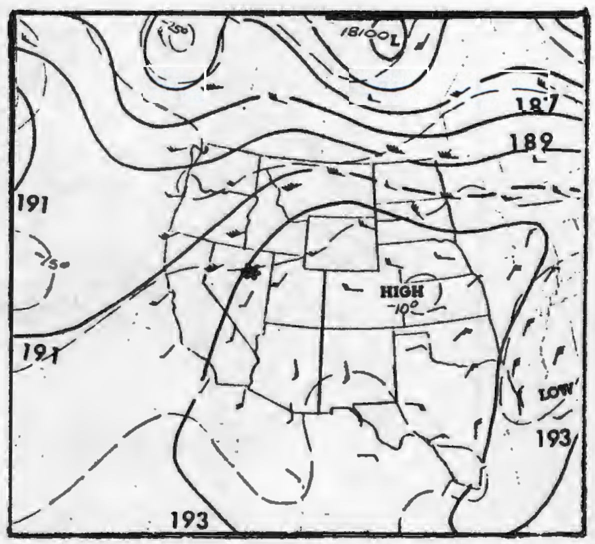
a.Aug. 26, 1970 Sea Level 1200 GMT



b.Aug. 27, 1970 Sea Level 1200 GMT

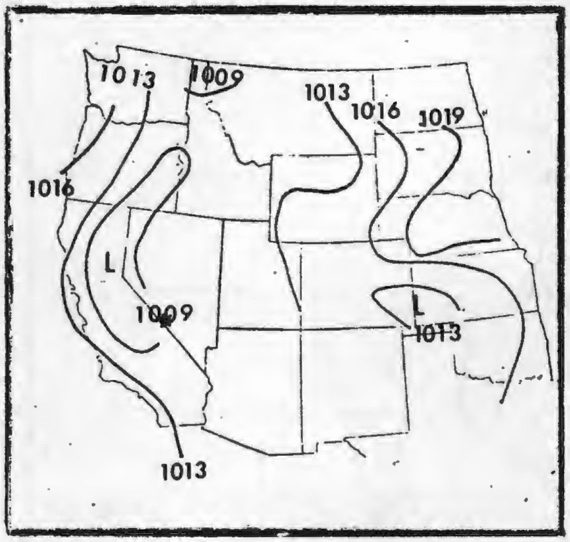


c.Aug. 28, 1970 Sea Level 1200 GMT

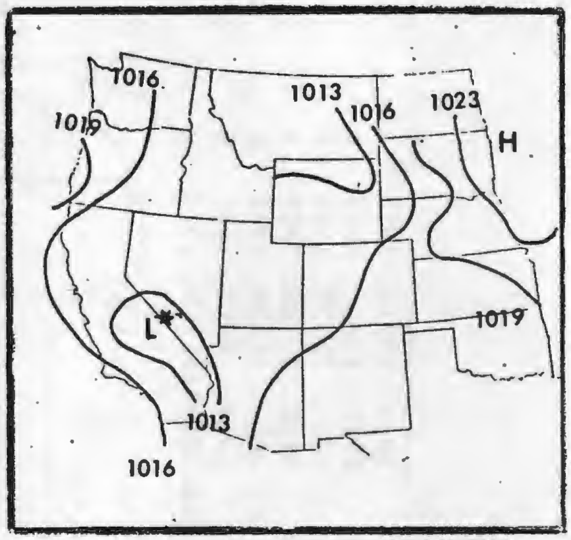


d.Aug. 27, 1970 500 MB 1200 GMT

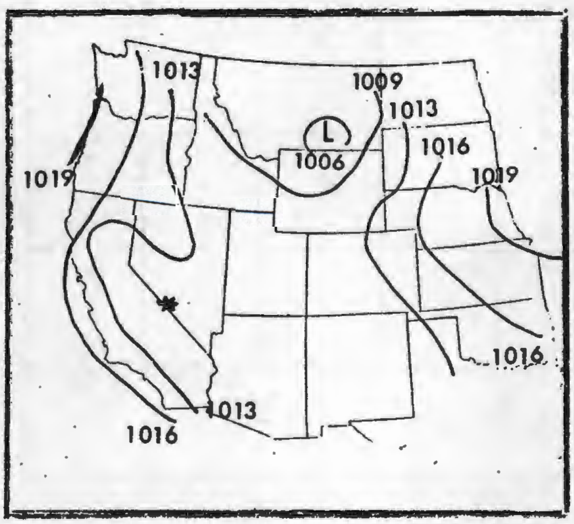
Figure 17.--Weather maps for Elko, Nevada, storm, Aug. 27, 1970



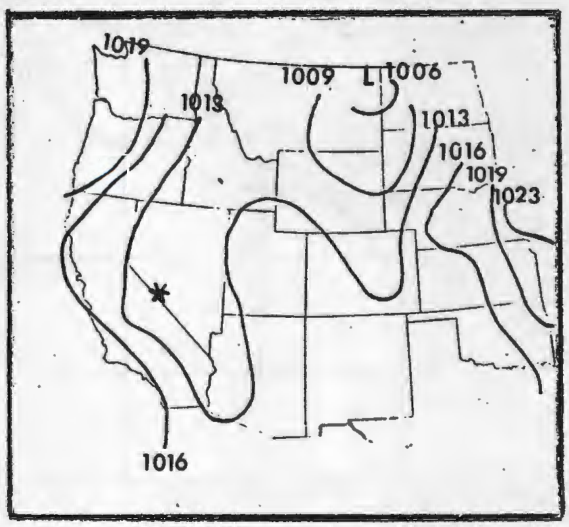
a. Aug. 10, 1890 Sea Level 0100 GMT



b. Aug. 10, 1890 Sea Level 1300 GMT



c. Aug. 11, 1890 Sea Level 0100 GMT



d. Aug. 11, 1890 Sea Level 1300 GMT

Figure 18.--Weather maps for Palmetto, Nevada, storm, Aug. 11, 1890

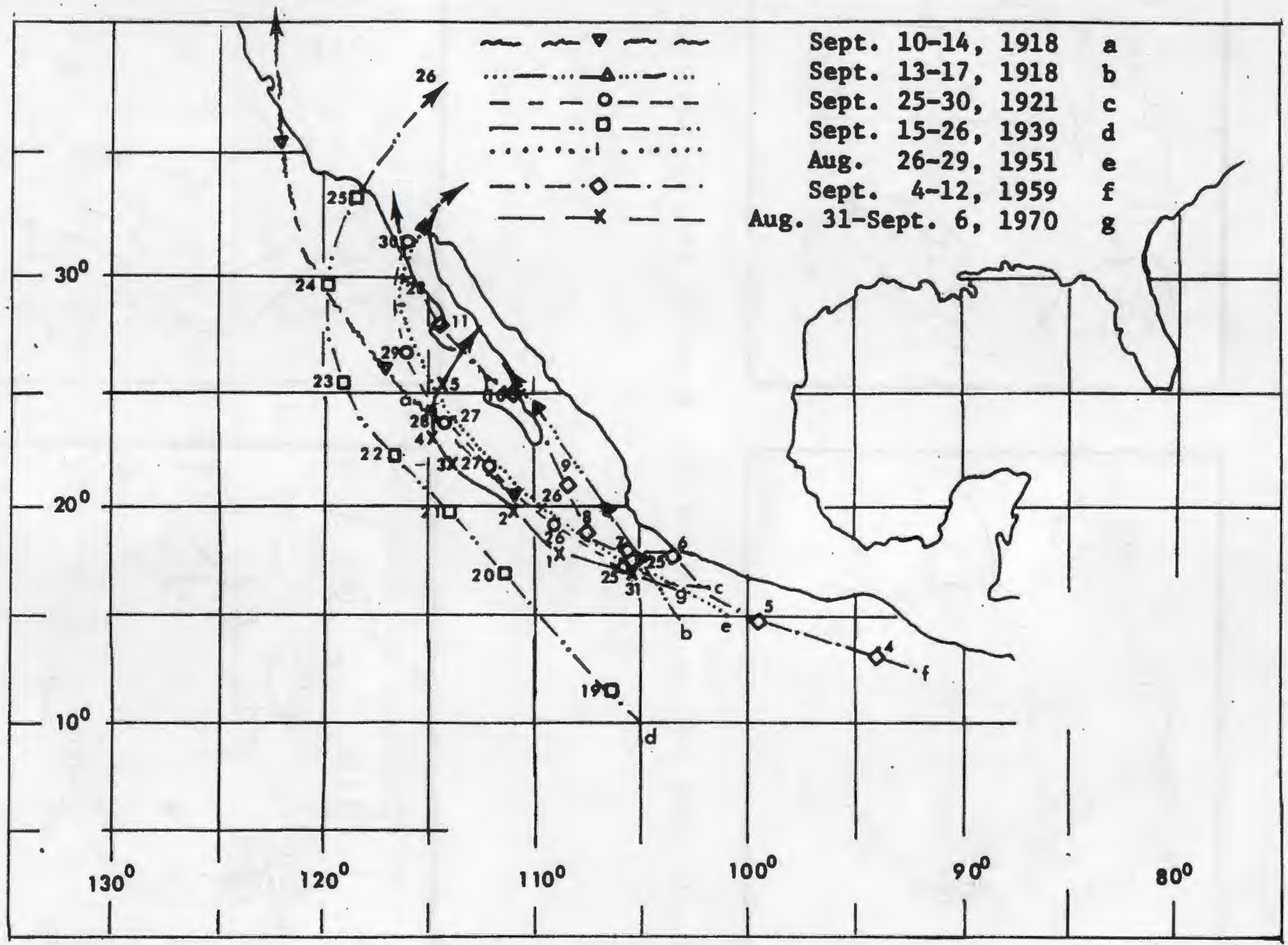


Figure 19.--Tracks of E. Pacific tropical storms.

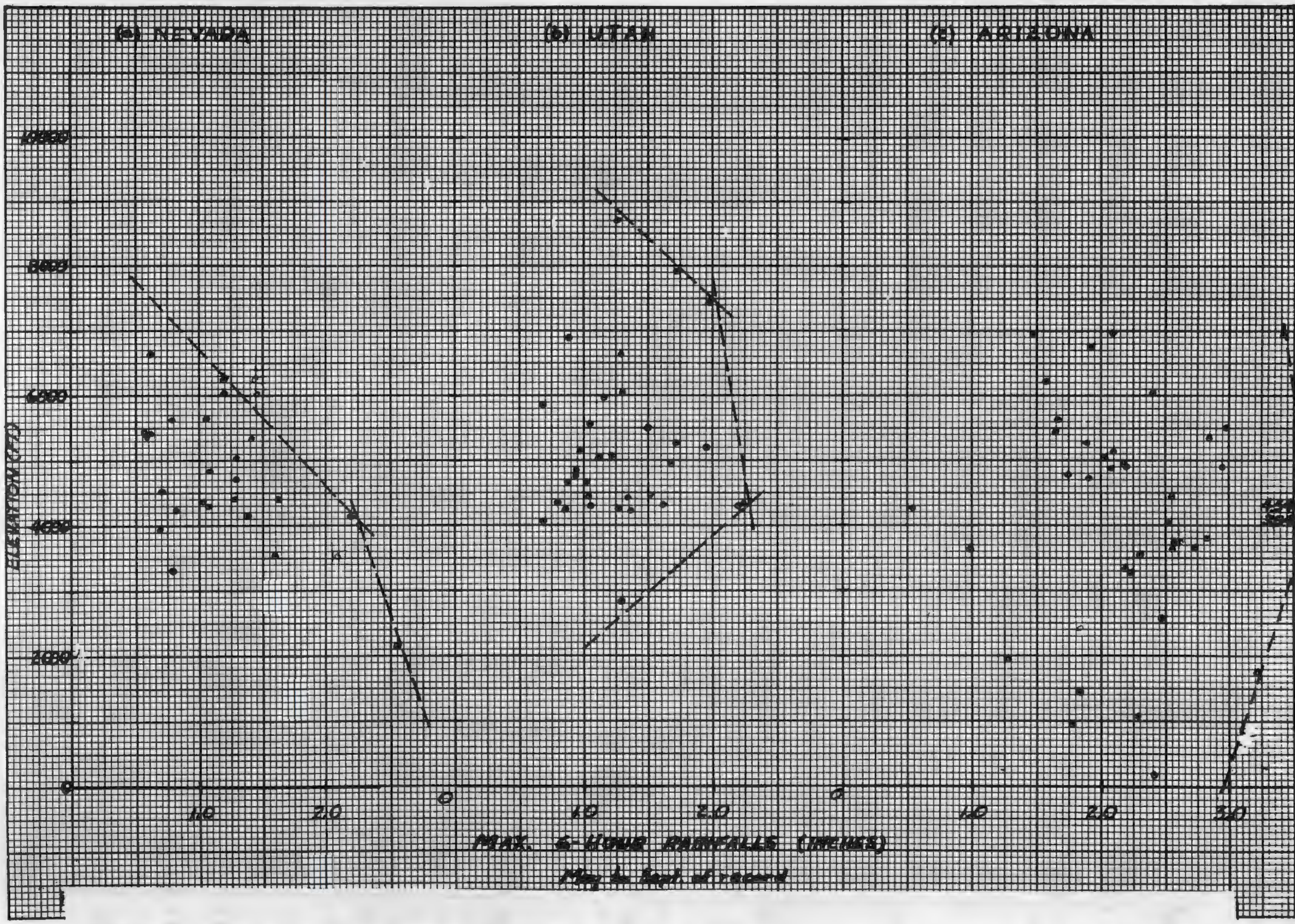


Figure 20.--Variation of maximum 6-hr summer recorder rainfall with elevation. (Envelope line dashed.)

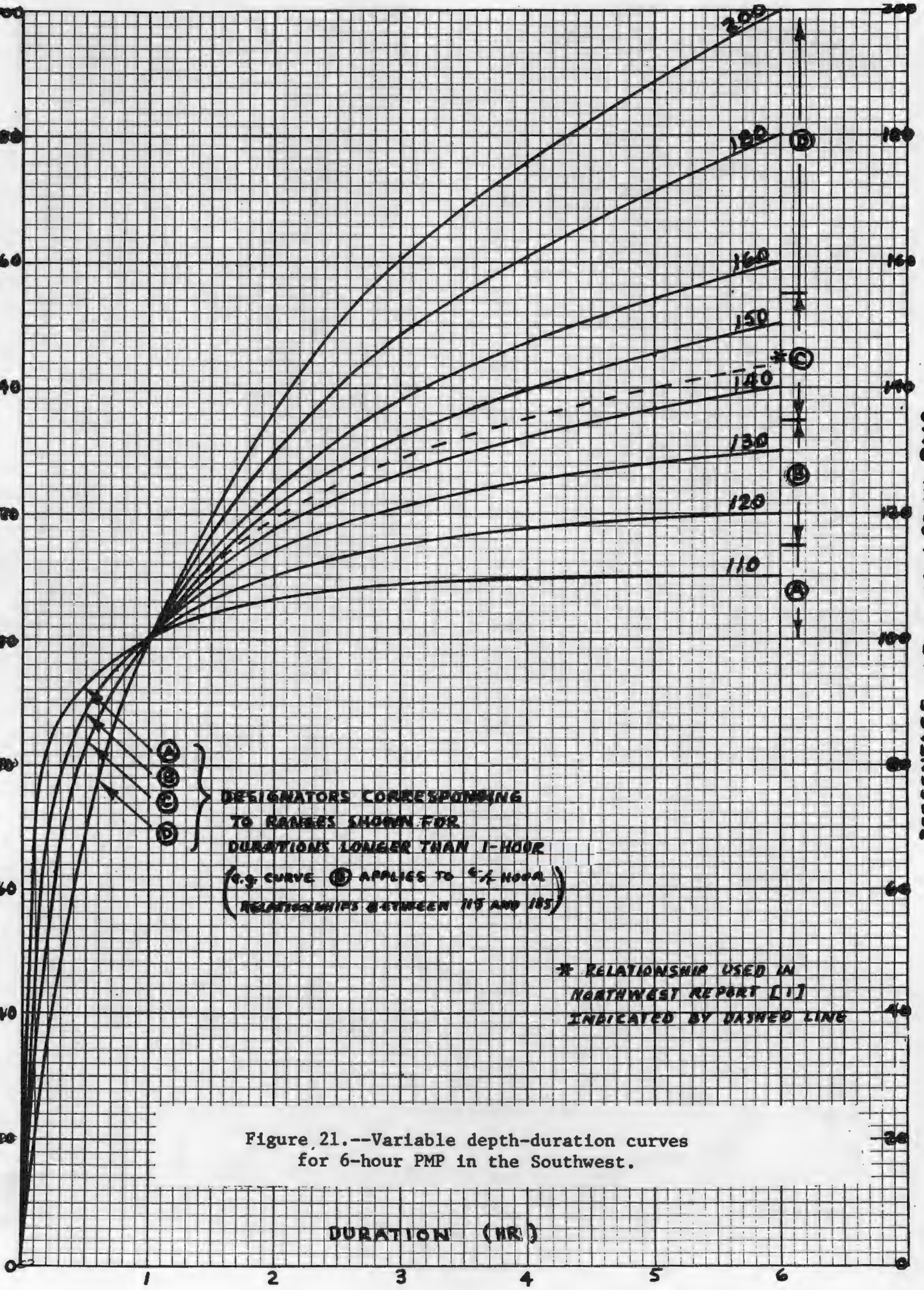


Figure 21.--Variable depth-duration curves for 6-hour PMP in the Southwest.

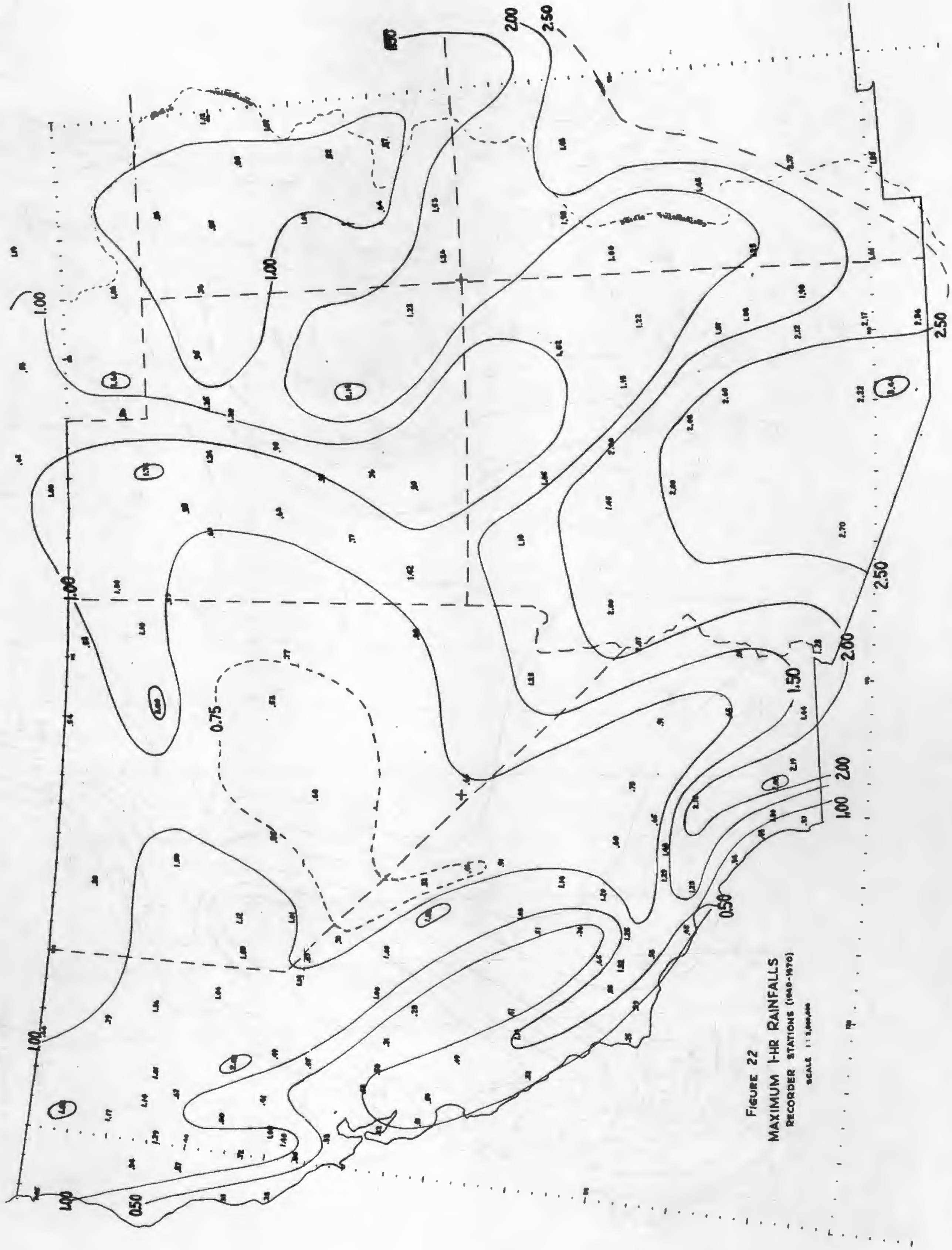


Figure 22
MAXIMUM 1-HR RAINFALLS
RECORDER STATIONS (1940-1970)
SCALE 1:2,000,000

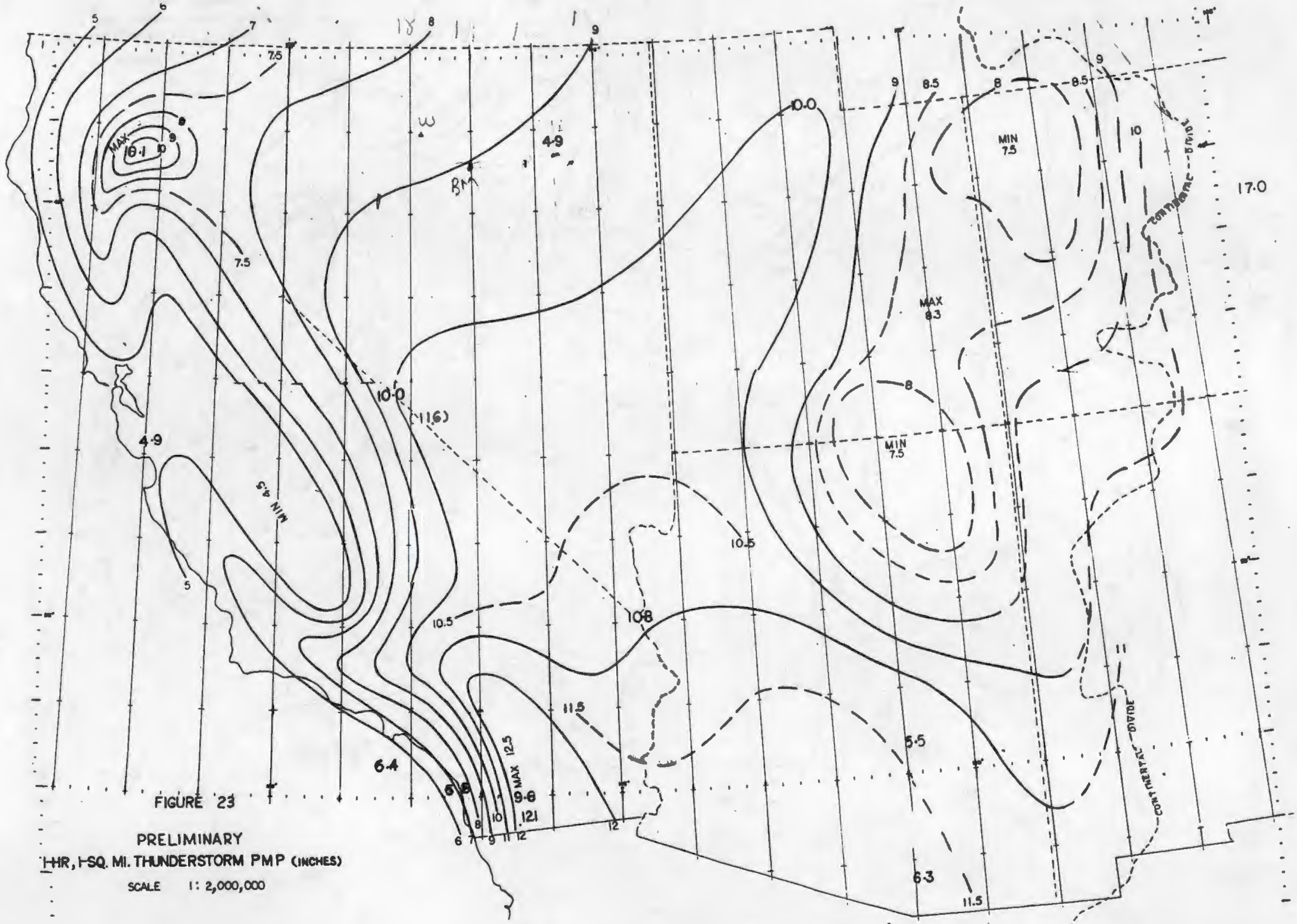


FIGURE 23

PRELIMINARY

1-HR, 1-SQ. MI. THUNDERSTORM PMP (INCHES)

SCALE 1: 2,000,000

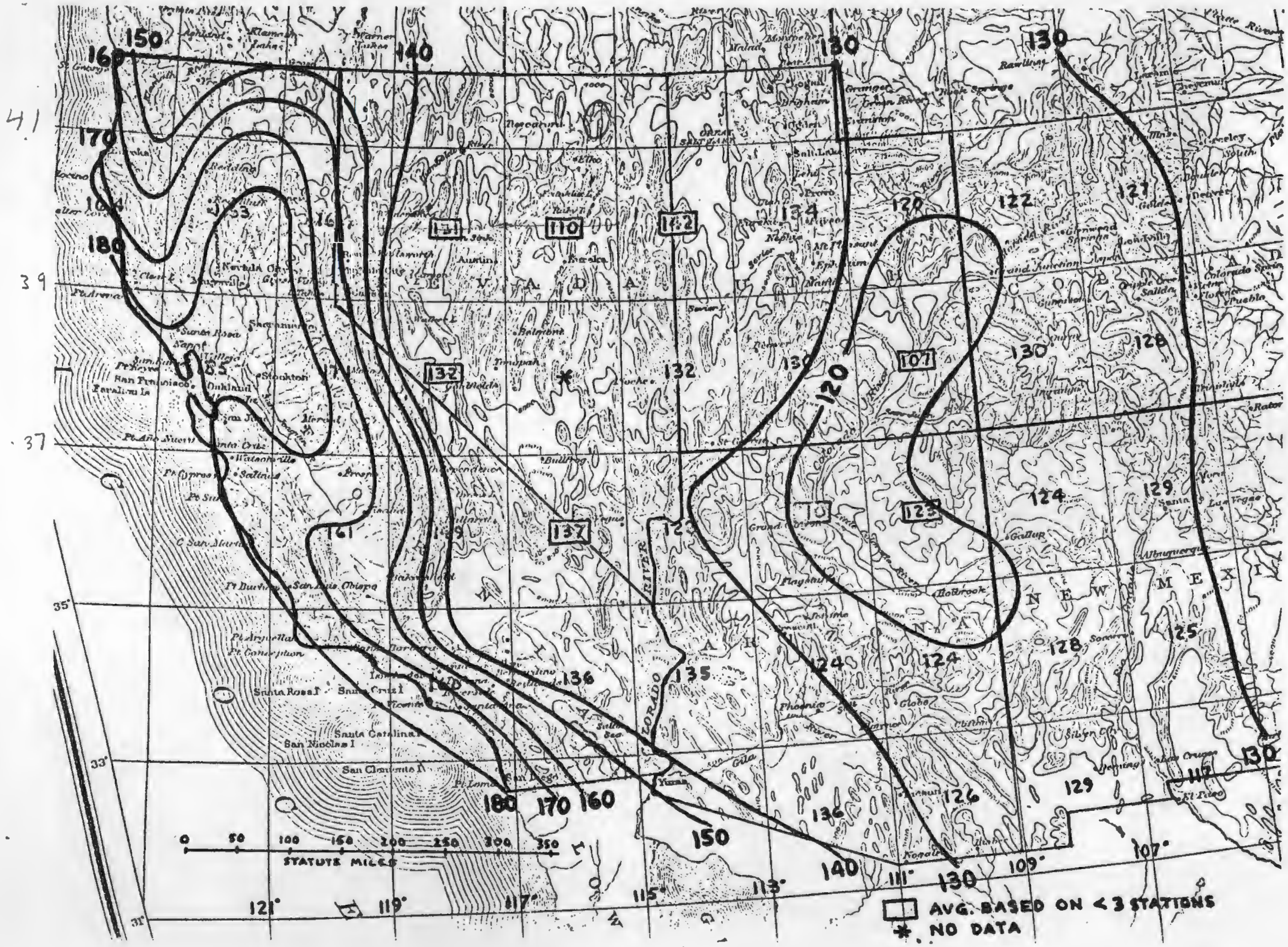


Figure 24.--Adopted 6-hour PMP in percent of 1-hour PMP. Averages based on 2° by 2° grid average of station data.

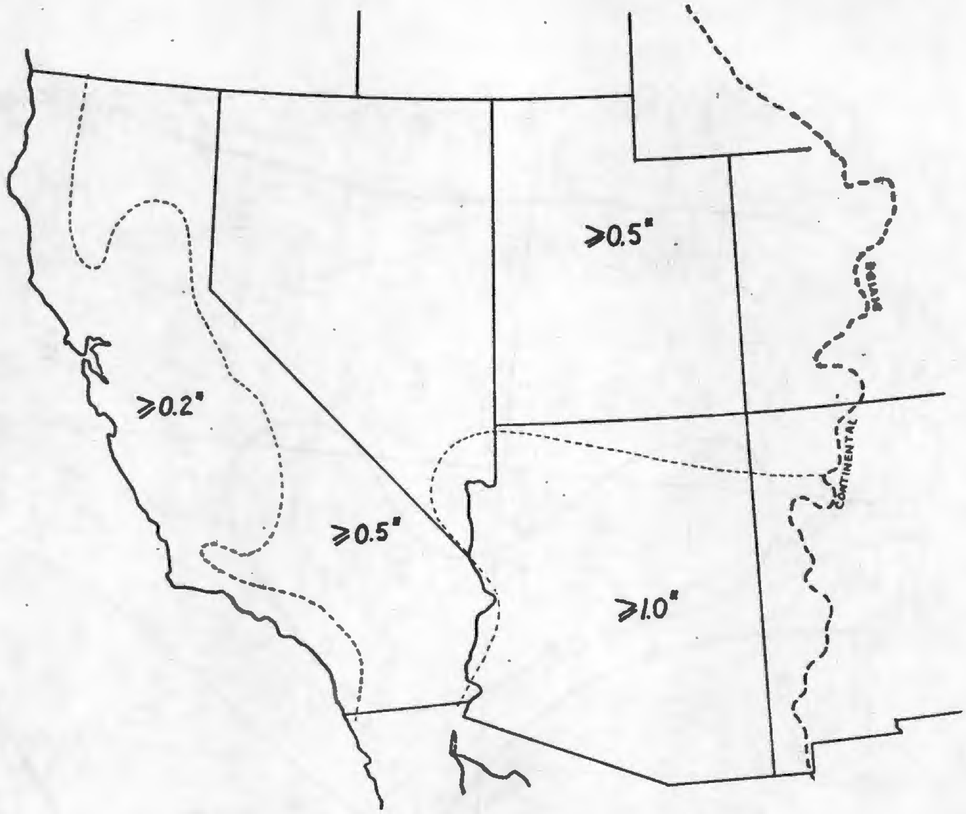


Figure 25.--Minimum 1-hr rainfall considered at recorder stations in study of 6-hr thunderstorms

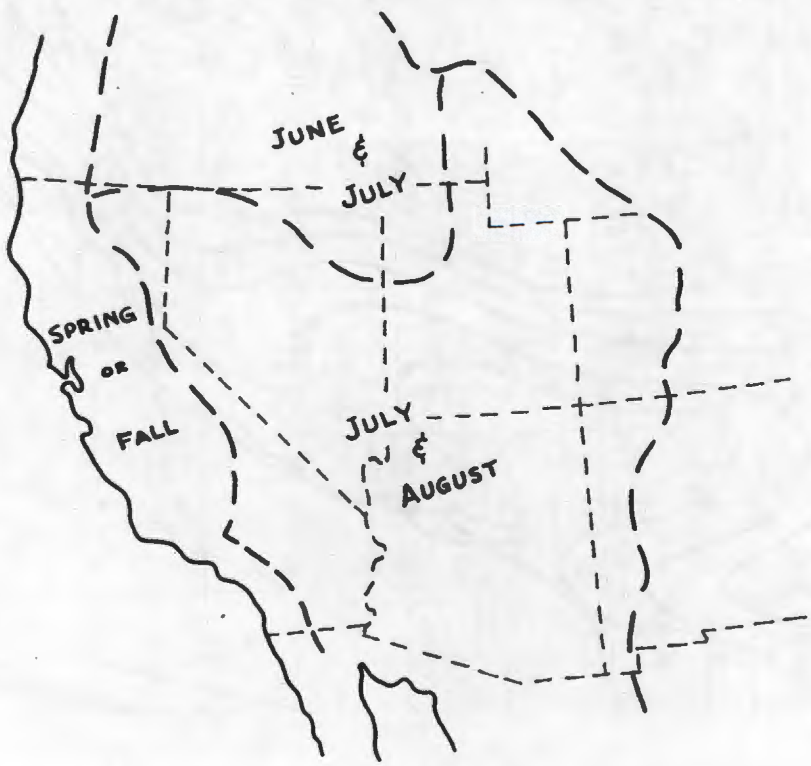


Figure 25a.--Regional variation of month of maximum thunderstorm rainfall.

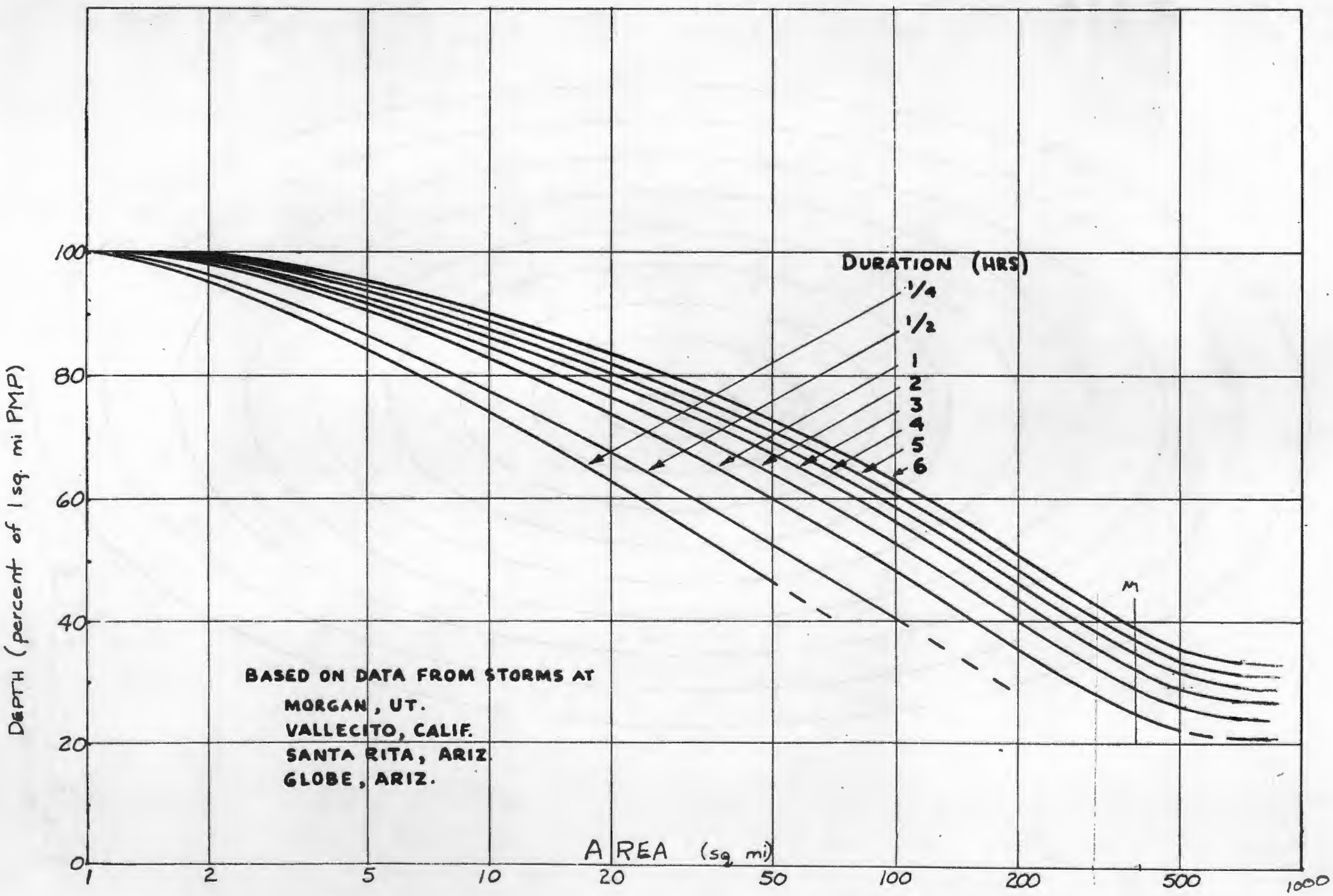
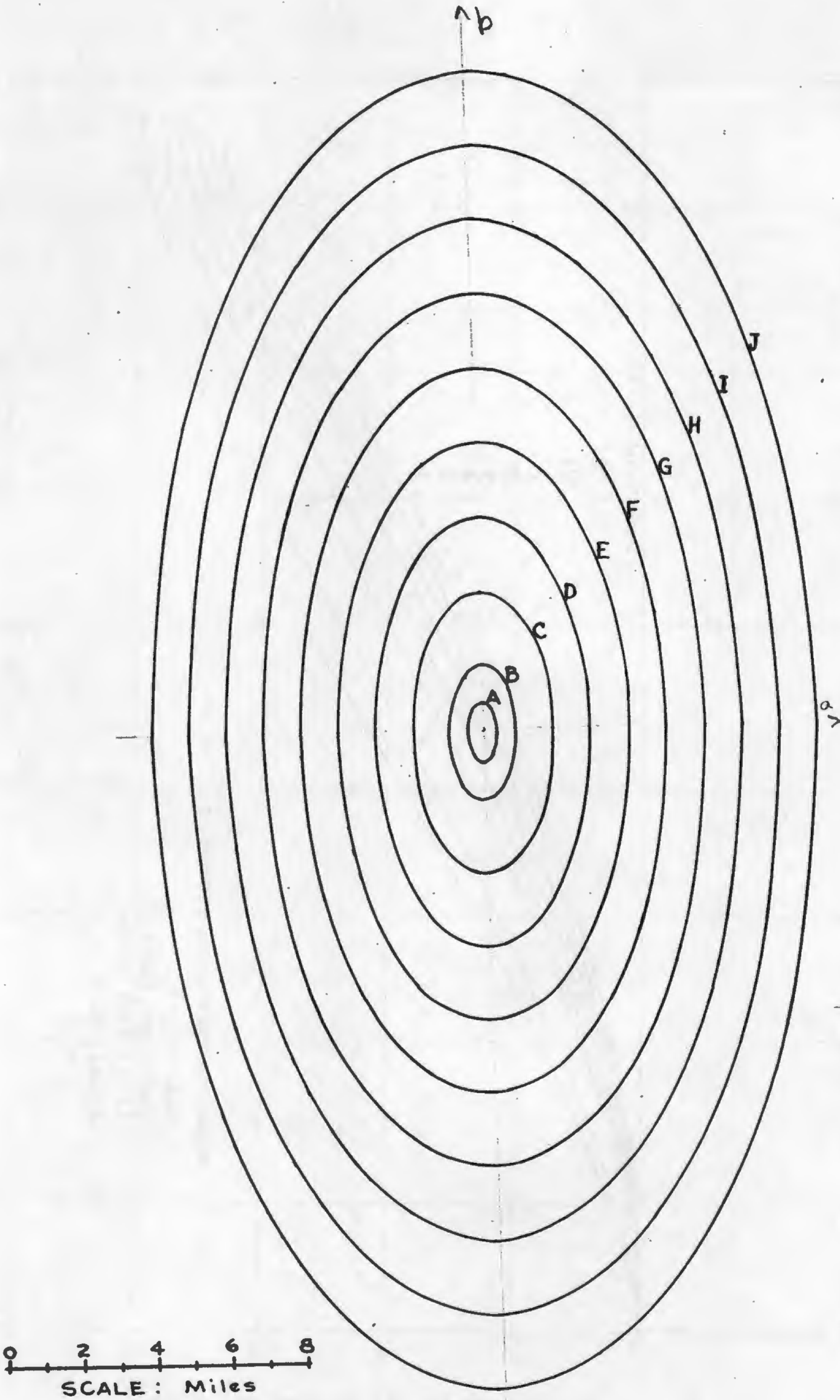


Figure 26.--Adopted depth-area relation for thunderstorm PMP in the Southwestern States



INCLOSED ISOHYETAL AREAS

LABELS		AREAS (SQ. MI.)
A	1	1
B	4	5
C	20	25
D	30	55
E	40	95
F	[illegible]	150
G	70	220
H	80	300
I	85	385
J	115	500
Σ	510	

Dimensions

Label	a/b mi
A	.8/1.6
B	1.8/3.6
C	4.0/8.0
D	5.9/11.8
E	7.8/15.6
F	9.8/19.6
G	11.8/23.6
H	13.8/27.6
I	15.7/31.4
J	17.8/35.6

Figure 27.--Prototype thunderstorm isohyetal pattern.

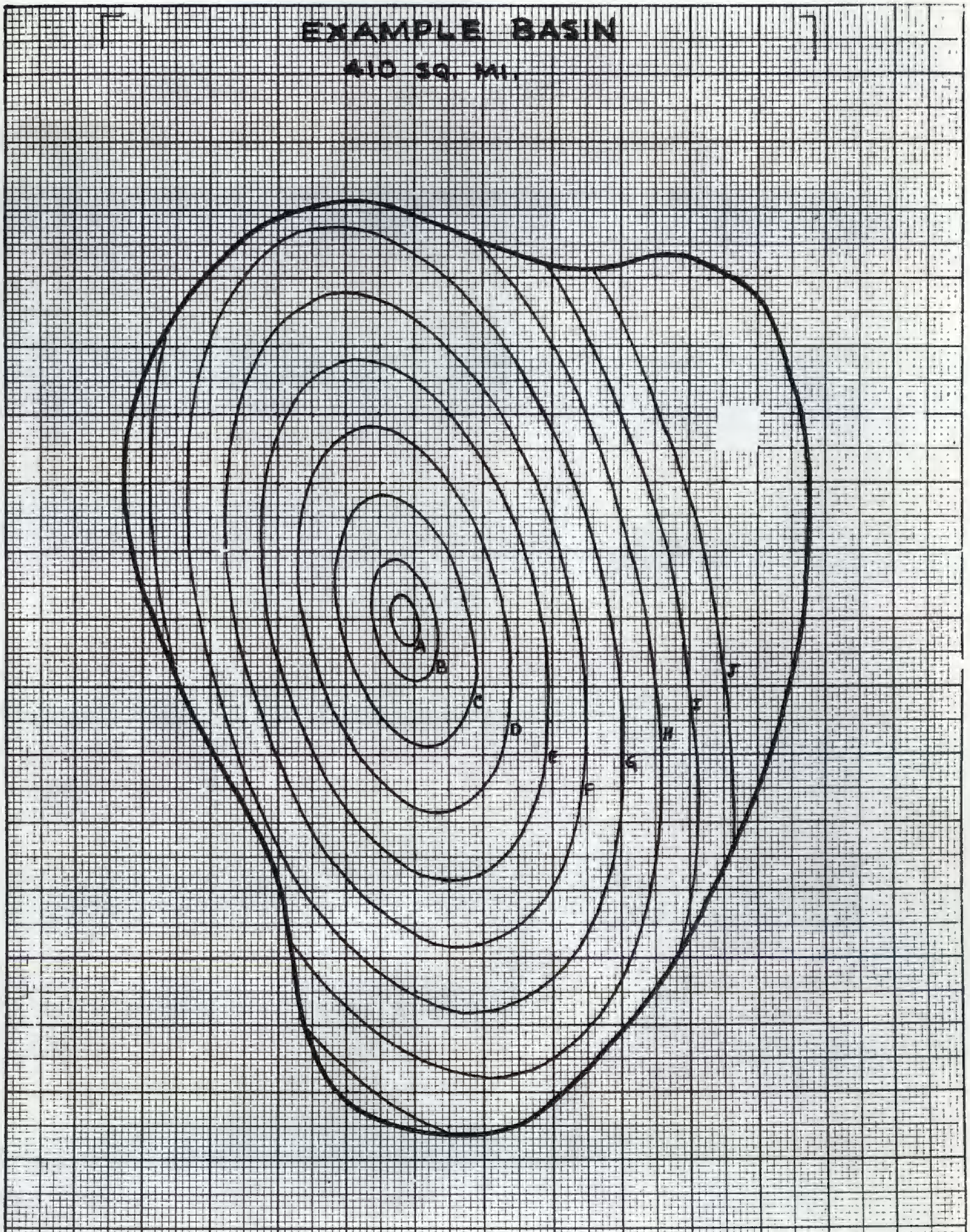


Figure 28.--Example showing fit of elliptical pattern to basin.

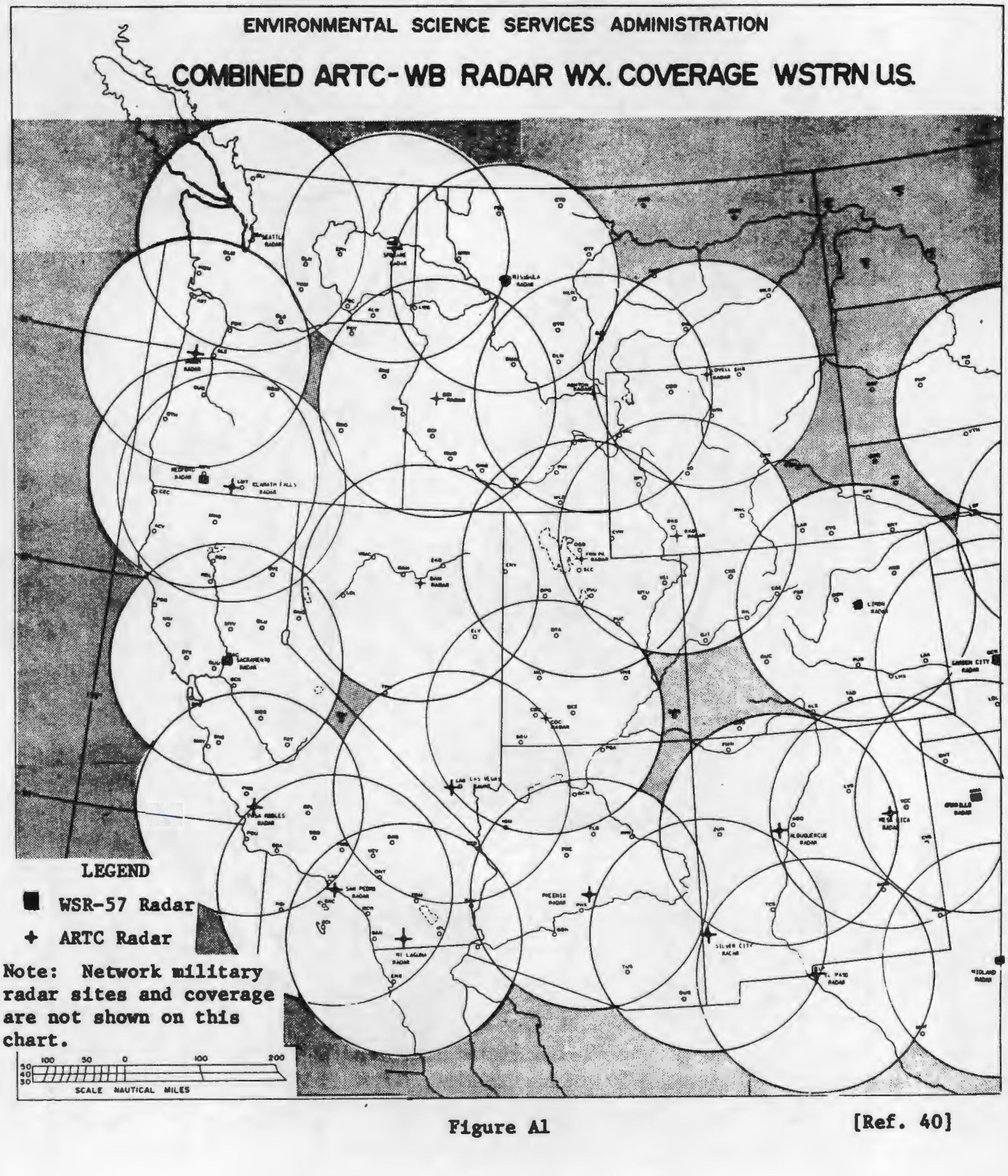


Figure A1 [Ref. 40]

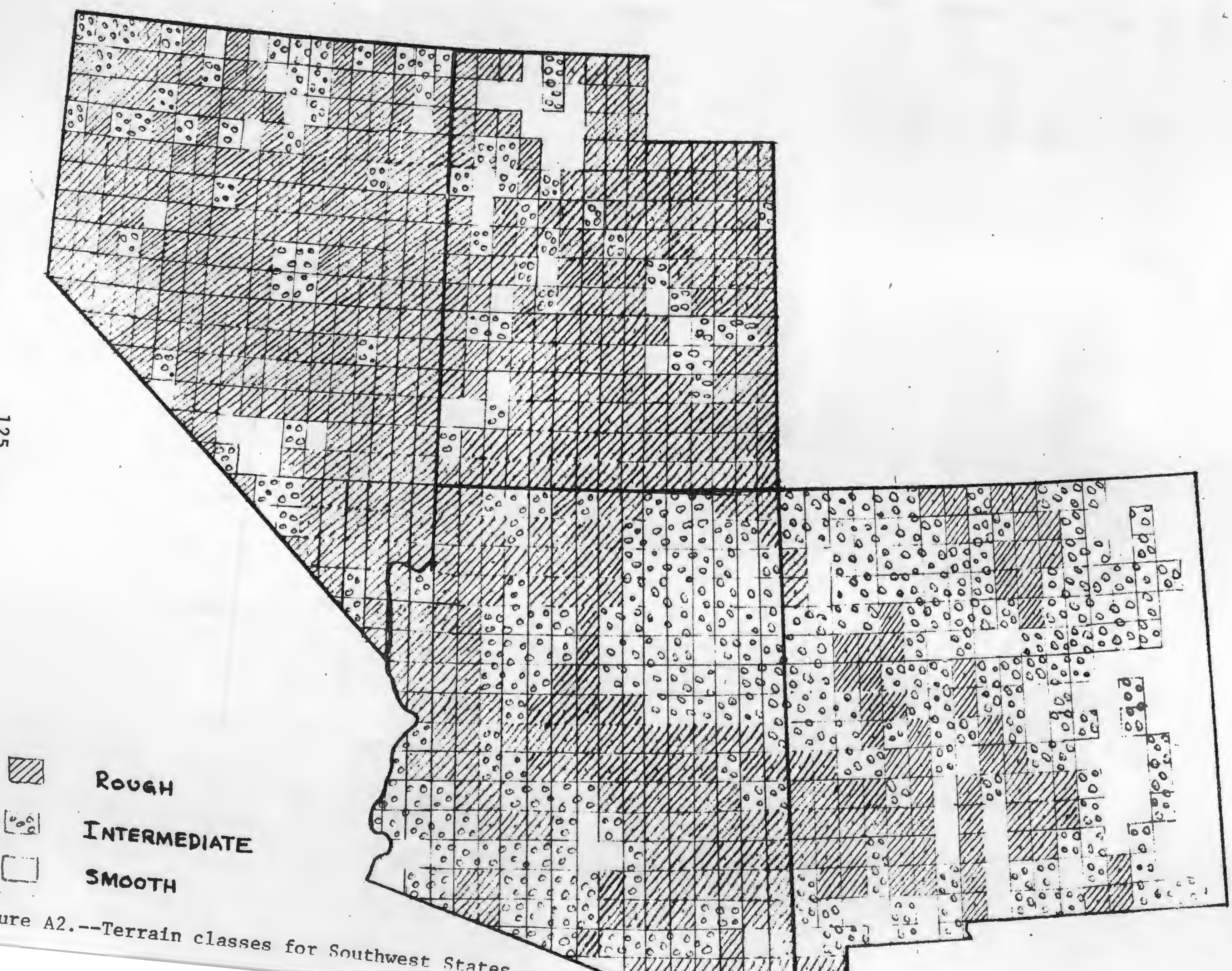


Figure A2.--Terrain classes for Southwest States.

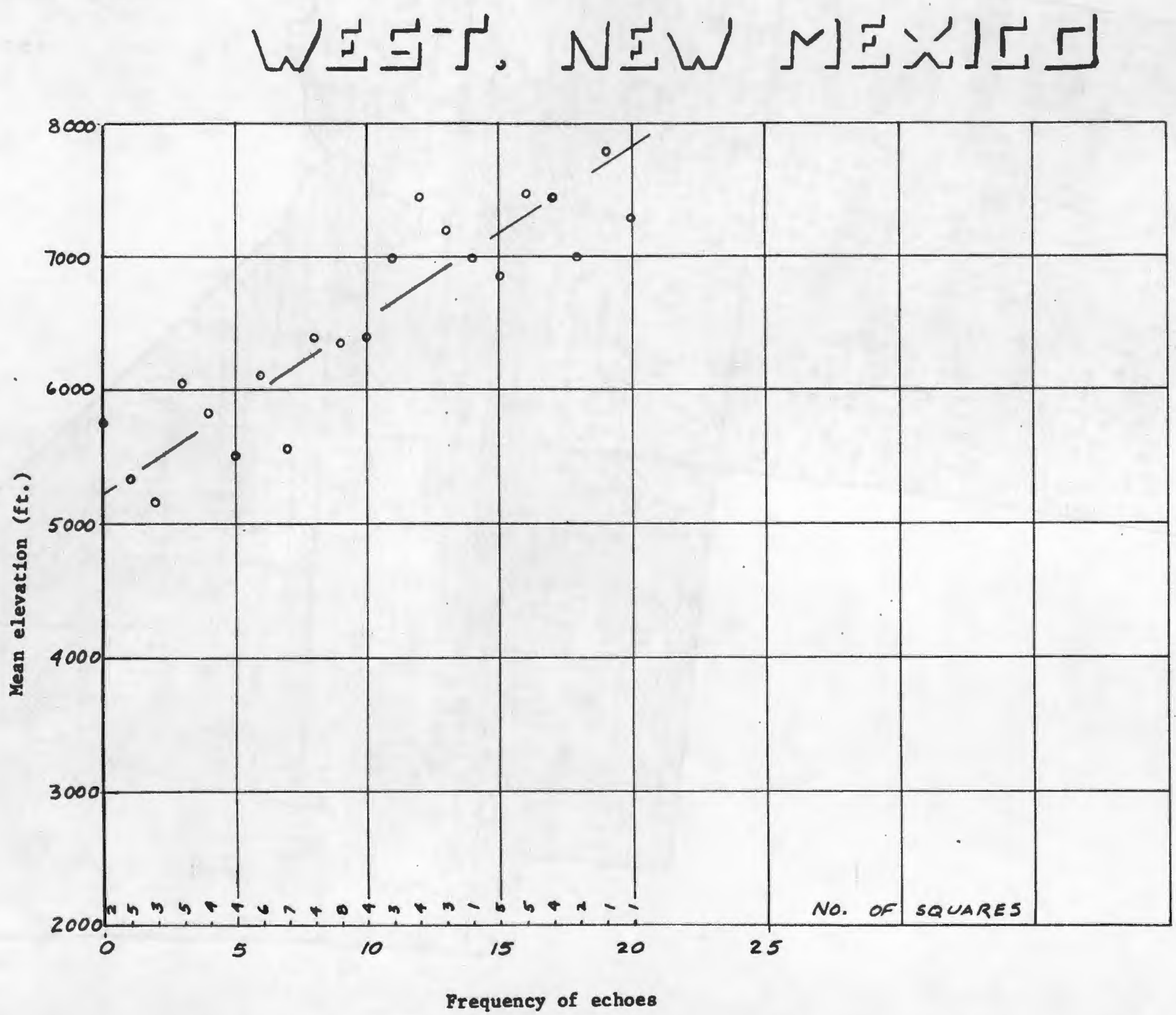


Figure A3.--Relationship between terrain elevation and echo frequency, W. New Mexico.

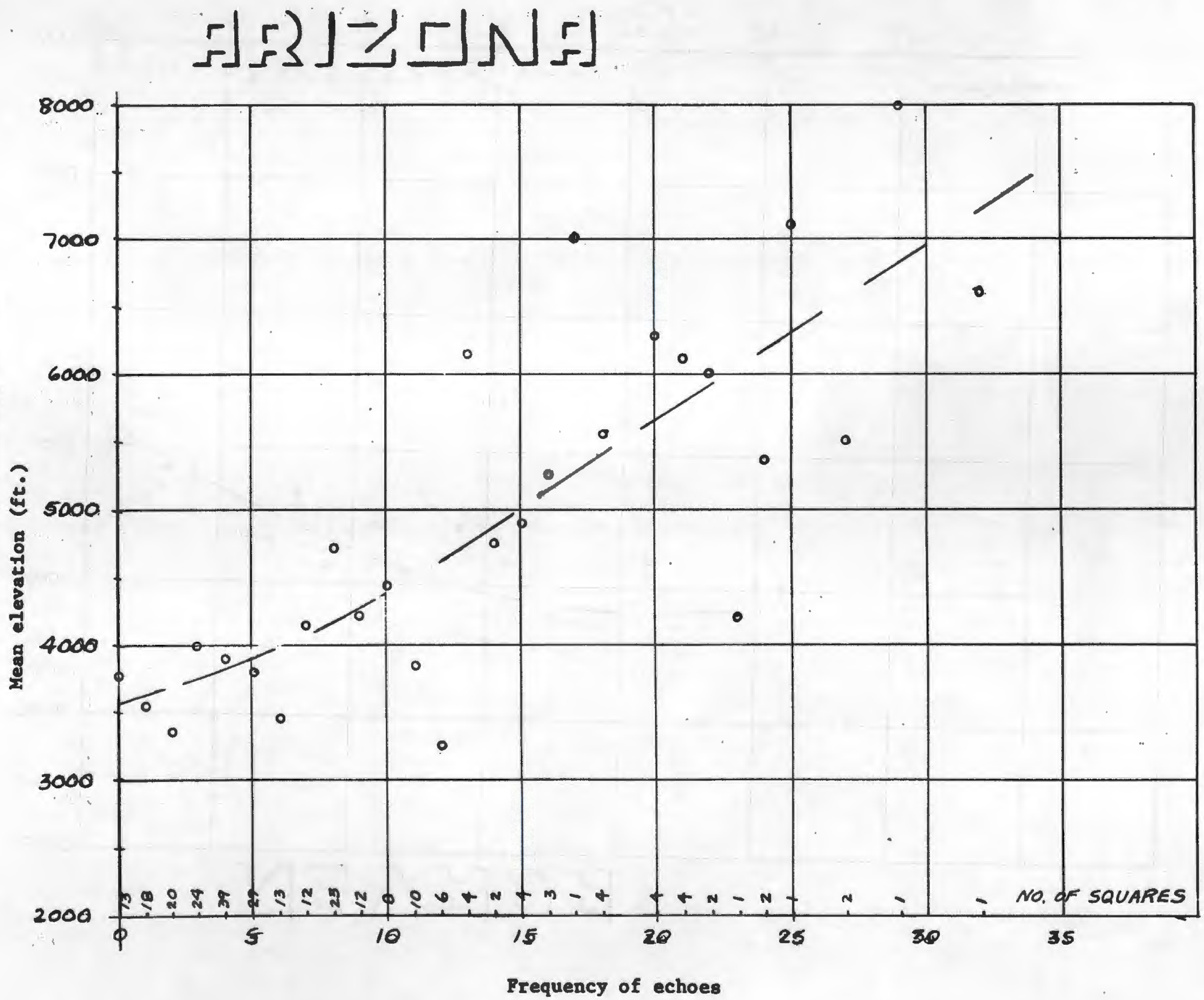


Figure A4.--Relationship between terrain elevation and echo frequency, Arizona.

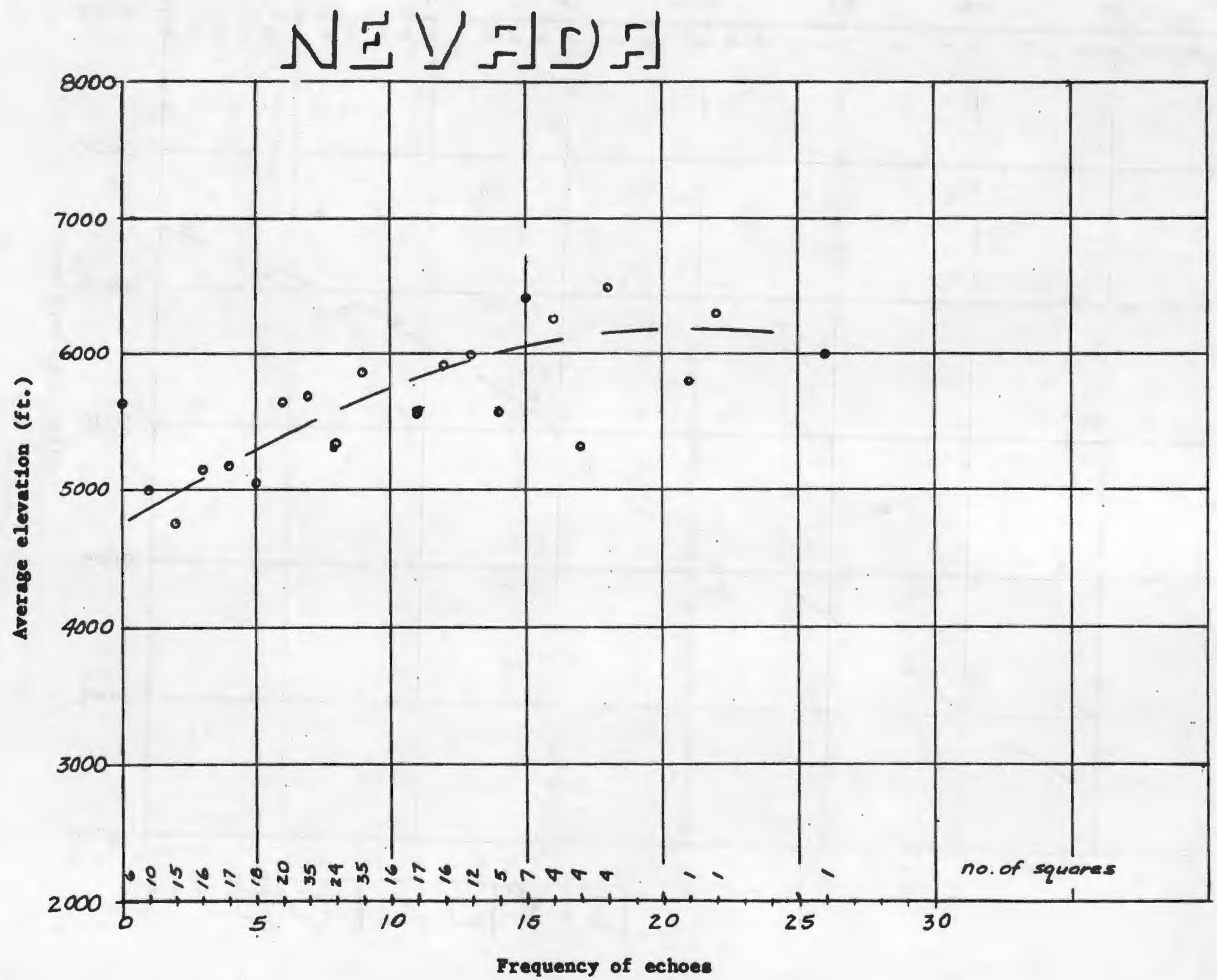


Figure A5.--Relationship between terrain elevation and echo frequency, Nevada.

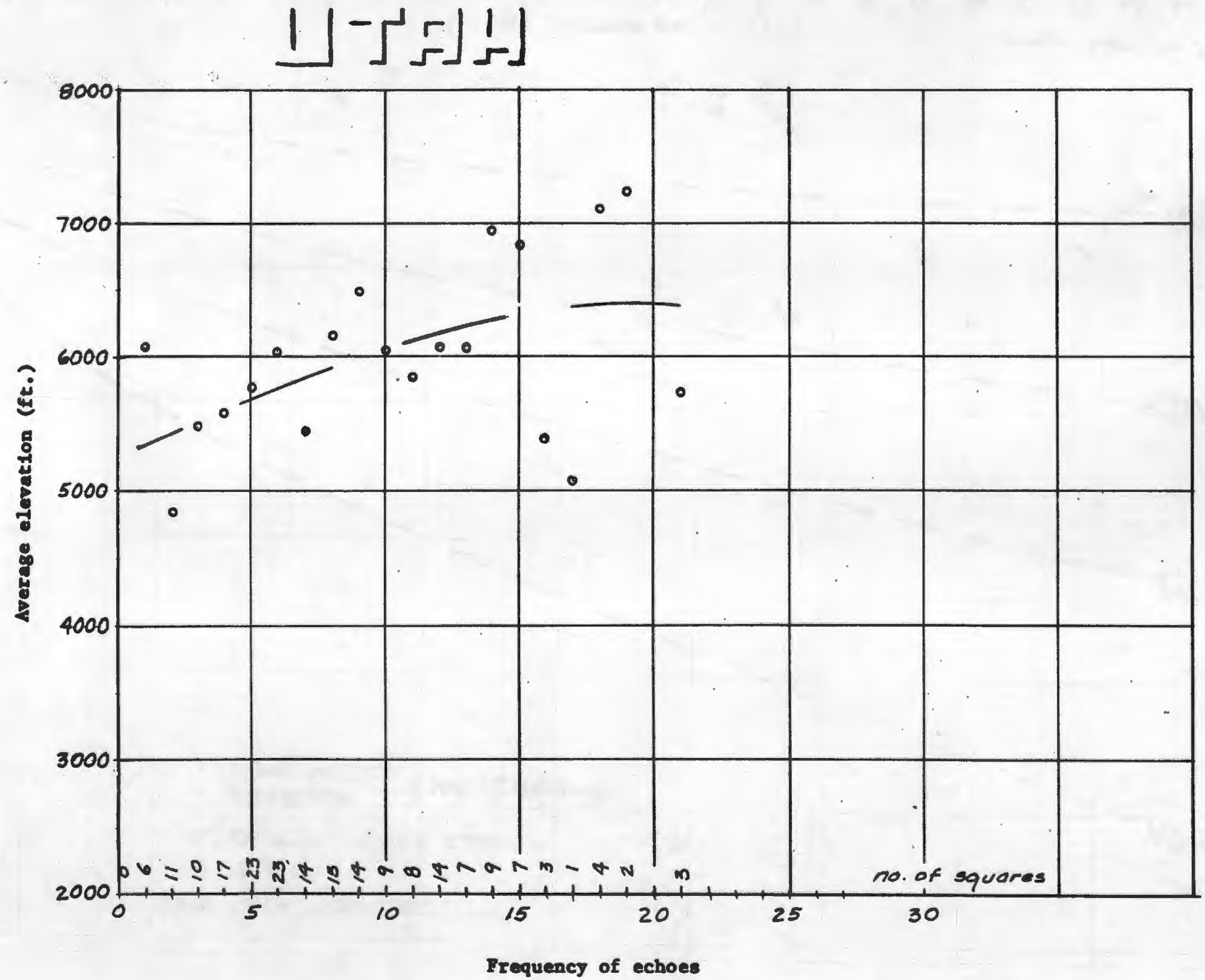


Figure A6.—Relationship between terrain elevation and echo frequency, Utah.

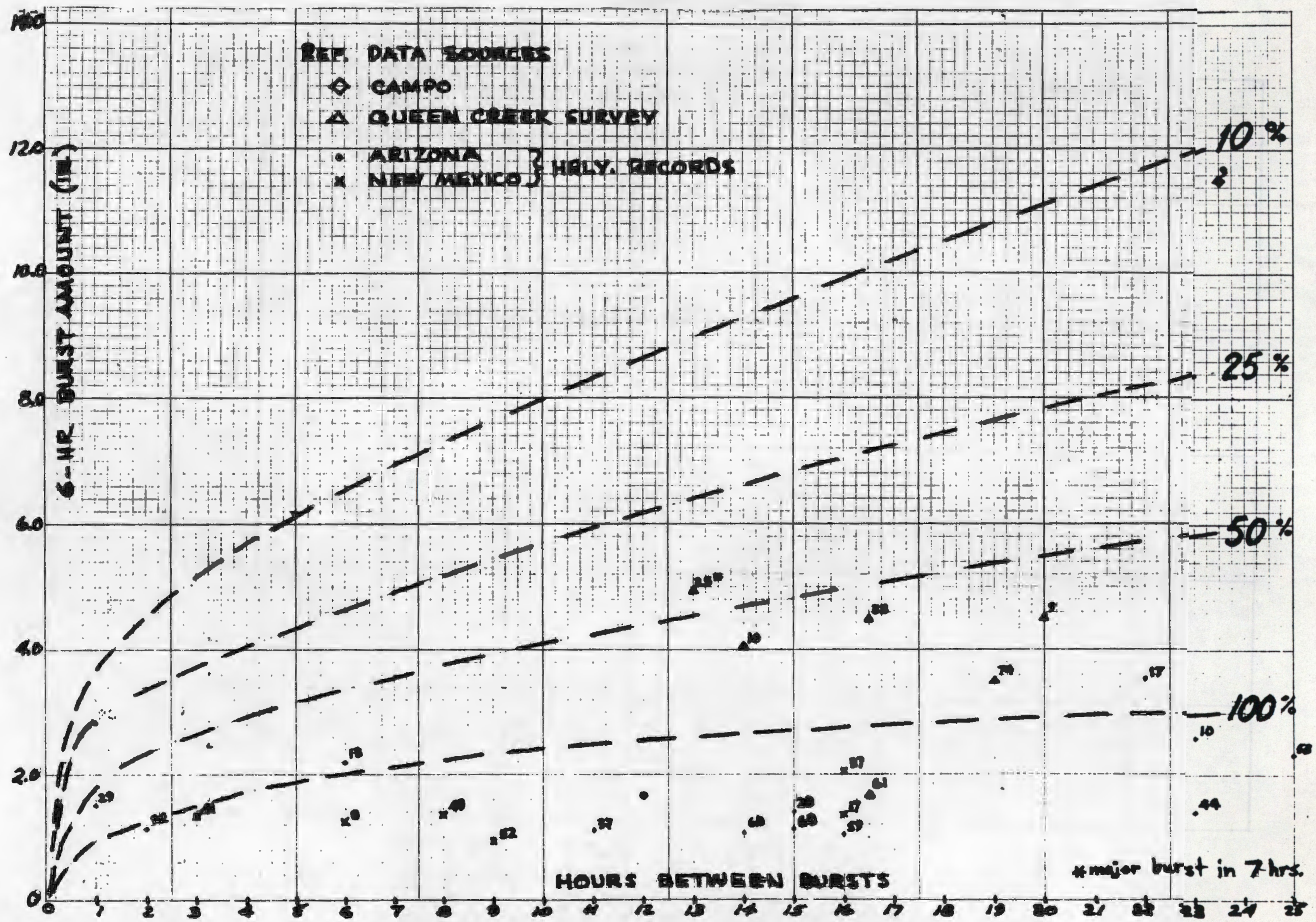


Figure B1.--Antecedent rainfall in Southwest warm-season storms. Plotted values indicate percentage. Antecedent rainfall is of 6-hr thunderstorm amount in inches.